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STUDY OF GAS TURBINE ADVANCES AND POSSIBLE MARINE APPLICATIONS

by

Carl Owen Brady

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by

CARL OWEN BRADY
Lieutenant Commander, United States Navy
B.S., University of Oklahoma
(1961)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREES OF
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and
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at the
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June, 1971

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by
CARL OWEN BRADY

Submitted to the Department of Naval Architecture and Marine Engineering and Department of Mechanical Engineering on June 4, 1971, in partial fulfillment of the requirements for the degree of Naval Engineer and Master of Science in Mechanical Engineering

ABSTRACT

The present status of marine gas turbine propulsion systems is reviewed with special emphasis on certain areas such as method of thrust reversal, enviromental problems, fuel requirements and cost considerations.

The future of marine gas turbine propulsion is considered by looking at the following:

1) Expected development of marine gas turbine engines
2) Thrust reversal methods
3) Suitability of gas turbine propulsion for different ship types

This is carried out by an extensive literature survey and personal interviews and/or correspondence with authorities in the gas turbine and marine engineering field.

Among the conclusions reached concerning the future of marine gas turbine propulsion are the following:

1) Most non-nuclear warships built in the future are expected to be propelled entirely by aero-derivative gas turbines.
2) A significant increase in the use of gas turbines for merchant ship propulsion utilizing both aero-derivative simple cycle and heavy duty regenerative engines is expected.
3) Primary method of obtaining thrust reversal with gas turbine propulsion is expected to continue to be through use of controllable, reversible pitch propellers. CRP propellers up to 40 to 50,000 HP per shaft for destroyer type ships and to over 60,000 HP per shaft for larger vessels are expected to be available in the next few years.
4) Marine gas turbine propulsion plant thermal efficiencies are expected to reach approximately these levels in the next decade:

Aero-derivative simple cycle gas turbine	38%
Heavy duty regenerative gas turbine	41
Combined gas turbine and vapor engine	49

Specific powers will also increase significantly.

Thesis Supervisor: A. Douglas Carmichael
Title: Professor of Power Engineering

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Special thanks are extended to my wife, Jean, for her help both in conducting the survey and in preparation of the manuscript. Also to both my wife and my children thanks for being extremely tolerant of an absent-minded and often neglectful husband and father during the last several months.

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The gas turbine has only recently been widely accepted in naval applications and is still quite infrequently utilized for merchant ship propulsion. The gas turbine appears to offer several advantages as a marine propulsion unit. Among these are low specific weight and volume, ease of automation, fast starting and reliability. It also possesses some disadvantages which have held back its widespread adaptation as a marine power plant. The major disadvantage probably has been its comparatively low thermal efficiency, particularly bad at part load, coupled with the requirement to burn a relatively high cost distillate fuel such as JP5 or diesel. Another important consideration involved with using gas turbines for marine propulsion is that the gas turbine is normally a uni-directional prime mover and therefore reversing of the ship can not be accomplished simply by reversing the direction of the prime mover rotation as with a diesel engine, for example.

In some applications the advantages of the gas turbine far outweigh the disadvantages and it has long been recognized as the obvious choice for the propulsion unit. The foremost example of this is in propulsion of unconventional craft such as hydrofoils or hover craft, the low specific weight requirements for these craft have virtually ruled out any prime mover other than the gas turbine. In other applications the choice has not been as clear. However, one other area where the gas turbine seems to be accepted is in supplying "boost power" for

naval vessels. Most naval war ships spend much of their operating life cruising at low power levels and only require high power for short periods of time. The gas turbine is very well suited to supply this boost power and has gained wide acceptance in this application. The acceptance of the gas turbine for base load cruising power has not been as great and this has resulted in several types of combined plants being used aboard naval vessels. These combined plants are designated by acronyms which have become part of the marine engineer's vocabulary. Some of the most important are:

Combined Diesel and Gas Turbine	CODAG
Combined Diesel or Gas Turbine	CODOG
Combined Steam and Gas Turbine	COSAG
Combined Gas Turbine and Gas Turbine	COGOG

The last combined plant listed utilizes a lower power gas turbine to supply the base load power and a high power turbine to supply the boost power. This allows both turbines to operate at their optimum efficiency and avoids poor part load performance.

In non-naval vessels, other than the unconventional types previously mentioned, the disadvantage of the high specific fuel consumption and high cost fuel have combined to keep commercial marine gas turbine installations quite infrequent.

There are two rather different types of gas turbines

which have been utilized as marine gas turbines. One of these is the industrial or heavy duty gas turbine which was originally designed for land based application such as electric power generation, large compressor prime movers and etc. The other type is the aircraft derivative gas turbine which is converted from an engine originally developed for aircraft propulsion. The aircraft derivative turbine is usually a high pressure ratio simple cycle turbine where as the heavy duty turbine generally utilizes a lower pressure ratio and often is a regenerative cycle engine. In general, the aircraft derivative turbine tends to be lighter and more compact than a heavy duty turbine of comparable horse power, but the heavy duty turbine, because of its heavier construction, tends to have a longer time between required overhauls.

The purpose of this study is to review the current status of marine gas turbines and to look at recent developments in gas turbine plants and associated propulsion equipment in order to gain some insight as to the future of marine gas turbine propulsion both naval and commercial. This has been carried cut by means of an extensive literature search and analysis and by personal interviews and/or correspondence with authorities in the marine engineering and gas turbine field.

Only open cycle plants are considered and no consideration is given to nuclear powered gas turbines.

In this section, some of the history and the present condition of marine gas turbine propulsion applications is discussed in three parts: the actual ship installations, the gas turbine engines and areas of specific interest such as reversing problems, low thermal efficiencies, and etc.

2.1. Ship Installations

The history of the gas turbine in marine propulsion is a comparatively short one. Apparently the first vessel to be propelled at sea by a gas turbine was the British motor gun boat (MGB 2009) in 1947. The purpose of this early application was to gain experience on design, installation, operation and maintenance of a gas turbine at sea. Following this installation, the British continued with patrol boat gas turbine installations with their Brave class patrol boats providing the model for several other patrol or gun boat propulsion systems.

Two other significant past applications were in the Auris and the John Sergeant, both merchant ships. The British tanker Auris (1) initially had four diesel driven alternators for electric propulsion. In 1951 one diesel was replaced by a 1200 hp British Thompson Houston gas turbine. This turbine operated 20,000 hours at sea with little down time. Deposition and corrosion of blades when burning high viscosity residual fuels was the greatest problem encountered with the high

pressure turbine (turbine inlet temperature was about 1200° F). The electrical propulsion system was replaced by an AEI 5500 hp gas turbine plant with a reversing gear and a hydraulic transmission unit in 1956. This plant was operated for over 5,000 hours. The maneuvering capability of Auris was very good but some problems were encountered with the friction clutches in the hydraulic transmission system. The Auris was withdrawn from service in 1960, not because of any difficulty with the propulsion plant, but because 12,000 ton tankers had become uneconomical.

The John Sergeant (2) was one of four Liberty ships converted under the U.S. Maritime Administration's program of investigation of different types of propulsion systems. It was powered by a two shaft 6000 hp G.E. heavy duty regenerative gas turbine (turbine inlet temperature about 1450° F) driving a controllable pitch propeller through a reduction gear. The gas turbine was capable of burning certain types of residual fuel for which a fuel treatment plant was carried on board. The John Sergeant went into service in 1956 and operated at sea for 9,270 hours. During this time very few malfunctions occurred and overall availability of the plant was estimated at 99.7 per cent. The only special problem was the fuel cleaning and treatment system. This system performed well but required careful and continuous attendance on the part of operating personnel. It was felt that unfavorable washing arrangements due to conversion compromises were

in large part responsible for this. The John Sergeant was removed from service in 1959 because of termination of the Liberty ship development program.

In the past decade the total installed marine gas turbine horsepower has increased dramatically. In the four years from 1965 to 1969 alone the installed horsepower increased by about a factor of three from 1.9 million to 5.8 million horsepower (3). Part of this is for electrical power generation and auxiliary use but most of it, about 95%, is for propulsion. Table 2.1 is a tabulation of most of the significant marine gas turbine propulsion applications presently in service or in a building program. From an examination of this summary some interesting points can be noted:

1) The USSR accounts for almost one-half of the total installed horsepower.
2) Most of the installations are in naval ships of the frigate/destroyer class or patrol boats and is mostly of the "boost" power variety.
3) Most marine installations (at least for those that are known; this excludes USSR) utilize gas turbine engines of the aircraft derivative type.

The Russian warship gas turbine installation details are not available. These details have been the subject of speculation in the literature. At least one source (4) states

TABLE 2.1 - Significant Marine Gas Turbine Propulsion Applications (Ships in service or in building program) (3)

Country Type ship	Δ,tons	L,ft.	V,kts	No. ships	Prop.	Manuf.[1]	Turbine Desig.	HP per Turbine	Turb. /ship
AUSTRALIA									
Ro-Ro	-	-	-	2	GT	GE	MS5212R	17,500(Ba)[2]	1
BRUNEI									
Patrol Boat[3]	114	90	54	1	CODOG	RR	Proteus	4,250(Bo)	3
CANADA									
DDH	4,200	398	27	4	COGOG	P&W	FT12A-3	3,700(Ba)	2
						P&W	FT4A-2	25,000(Bo)	2
HMCS Bras D'or	200	151	50+	1	CODOG	P&W	FT4	22,000(Bo)	1
Icebreaker	6,320	295	15	1	CODAG	W	W41	4,000(Bo)	2
DENMARK									
Frigate Peder Skram	2,720	396	30+	2	CODOG	P&W/SL	GC4	22,000(Bo)	2
FINLAND									
Corvette	600	228	30	2	CODOG	RR	Olympus	22,000(Bo)	1
FRANCE									
Frigate	2,000	335	25	1	CODAG	Turboma	M38	10,000(Bo)	1

TABLE 2.1 (continued)

Country Type ship	Δ,tons	L,ft.	V,kts	No. ships	Prop.	Manuf.	Turbine Desig.	HP per Turbine	Turb. /ship
GERMANY (FED. REP.)									
Frigate	2,550	337	-	6	CODAG	BBC	TA8007 NA10017	12,000(Bo)	2
Frigate(Koln class)	2,000	426	30	2	CODOG	-	-	15,000(Bo)	4
IRAN									
Frigate	1,200	310	38	4	CODOG	RR	Olympus	20,000(Bo)	2
ITALY									
DD (San Giorgio)	4,450	455	28	1	CODAG	Tosi/AEI	G6/2	7,500(Bo)	2
Frigate(Alpino class)	2,700	366	28	2	CODAG	Tosi/AEI	G6	7,500(Bo)	2
Gunboat	215	150	40	4	CODAG	RR	Proteus	4,250(Bo)	1
Gunboat	206	132	40	2	CODAG	AEI	G6	7,500(Bo)	1
JAPAN									
Patrol craft	380	190	26	1	CODAG	Mi	MUK-501	5,000(Bo)	1
LIBYA									
Frigate(MK 7)	1,500	310	38	1	CODOG	RR	Olympus	20,000(Bo)	2
MALAYSIA									
Frigate	1,600	308	30	1	CODOG	RR	Olympus	19,500(Bo)	1

TABLE 2.1 (continued)

Country Type ship	Δ,tons	L,ft.	V,kts	No. ships	Prop	Manuf.	Turbine Desig.	HP per Turbine	Turb. /ship
SWEDEN									
Torpedo Boat	200	140	40	12	GT	RR	Proteus	4,100(Ba)	3
UNITED KINGDOM									
Frigate (HMS Exmouth)	1,456	310	27	1	COGOG	RR RR	Proteus Olympus	3,500(Ba) 18,000(Bo)	2 1
DD (Type 42)	3,500	-	-	1+	COGOG	RR	Tyne Olympus	4,400(Ba) 27,200(Bo)	2 2
Frigate (Type 21)	2,300	-	-	1+	COGOG	RR	Tyne Olympus	4,400(Ba) 27,200(Bo)	2 2
Patrol Boat(Brave Cl.)	114	98	50+	2	GT	RR	Proteus	3,500(Ba)	3
Frigate (Tribal Cl.)	2,700	360	25+	7	COSAG	AEI	G6	8,250(Bo)	1
DD(HMS Bristol)	6,750	507	32	1	COSAG	RR	Olympus	22,300(Bo)	2
DD(Country Cl.)	6,200	520	32	1	COSAG	AEI	G6	8,250(Bo)	4
UNITED STATES									
PGH-1 (Hydrofoil)	57	75	40	1	GT	RR	Tyne	3,600(Ba)	1
PGH-2 (Hydrofoil)	58	72	40	1	GT	RR	Proteus	3,100(Ba)	1
PCH-1 (Hydrofoil)	110	115	45	1	CODOG	RR	Proteus	2,800(Bo)	2

TABLE 2.1 (continued)

Country / Type ship	Δ,tons	L,ft.	V,kts	No. ships	Prop	Manuf.	Turbine Desig.	HP per Turbine	Turb. /ship
PG 84 Class	240	165	40	17	CODOG	GE	LM1500	14,000(Bo)	1
AGEH (Hydrofoil)	310	212	50	-	CODOG	GE	LM1500	15,000(Ba)	2
USCG Hamilton Class	3,000	378	29	11	CODOG	P&W	FT4A	18,000(Bo)	2
DD (Spruance Class)	7,000	596	25+	30	GT	GE	LM2500	20,000(Ba)	4
Ro-Ro (Callaghan)	23,680	694	25.8	1	GT	P&W	FT4A	20,000(Ba)	2
Container	30,000	800	25+	4	GT	P&W	FT4A-12	30,000(Ba)	2
USSR									
DD(Kresta Class)	6,000	508	34	2	CODOGest	-	-	23,000(Bo)	4
DD(Kashin Class)	6,000	492	35	6	GTest	-	-	25,000(Ba)	4
DD(Kynda Class)	6,000	492	35	4	COSAGest	-	-	25,000(Bo)	2
DE(Petya Class)	1,050	262	30	30	CODOG	-	-	5,000(Bo)	2
DE(Mirka Class)	900	262	28	15	GT	-	-	5,000(Ba)	2
DE(Poti Class)	350	200	50	50	GTest	-	-	5,000(Ba)	2
Patrol Boat	150	131	40	50	GT	-	-	5,000(Ba)	2
Cargo	16,000	-	-	-	GT	LMZ	GTU-20	6,500(Ba)	2
ACV Sormovich	22	87	-	1	GT	Ivchenko	AL-24	2,000(Ba)	1

TABLE 2.1 (continued)

Notes:

1. Manufacturer abbreviations are as follows:

AEI	Associated Electrical Industries, Ltd.
BBC	Brown Boveri Corp.
GE	General Electric Co.
LMZ	Leningrad Metal Works
Mi	Mitsubishi Heavy Industries, Ltd.
P&W	Pratt & Whitney Aircraft Div. of United Aircraft Corp.
RR	Rolls-Royce Ltd.
SL	Stal-Laval Inc.
Tosi	Franco Tosi, S.p.A.
W	Westinghouse Electric Corp.

2. Applications are designated as follows:

Ba	Base power application
Bo	Boost power application

3. Several other countries have essentially this same boat in service.

that it is most likely that the Kashin-class destroyers are powered by aircraft derivative type turbines but no firm basis for this belief is offered. Some of the Russian commercial marine gas turbine application details are known. Both the tanker Yessentukiy (which does not appear to be currently in service), and the cargo ship Parizhskaya Kommuna utilize two heavy duty intercooled, regenerative two shaft 6500 hp gas turbines coupled in parallel through conventional articulated double reduction gears driving a single controllable reversible pitch propeller. (3, 5, 6). The turbine inlet temperature is about 1380° F with a pressure ratio of 9:1. Another commercial application is in the gas turbine hydrofoil craft Burevestnik, which is a 150 seat hydrofoil craft for use on rivers. It is powered by two CPK gas turbines of aircraft derivation developing 2,700 bhp at 1,070 rpm (7). These turbines are directly coupled to two-stage axial flow pumps which provide the hydraulic thrust propulsion. The ACV Sormovich is also powered by an aircraft derivative turbine, Ivchenko A1-24 (3). The aircraft version of the A1-24 is a single shaft turbo prop engine with a pressure ratio of 7:1, turbine inlet temperature of about 1800° F (8). A few other observations which should be considered in attempting to infer the nature of the Russian warship installations are:

1) The USSR has only very recently begun to utilize aircraft derivative gas turbines in land based electrical power generating plants for emergency and peak load performance (9).

2) The USSR does possess a number of high performance turbo jet, turbo prop, and fan jet engines suitable for conversion to marine propulsion use (8).

3) The horsepower per gas turbine in the USSR destroyer installations is much greater than in any of the commercial installations described above.

The many frigate/destroyer type installations are almost all of the combined type variety with most of them utilizing a prime mover other than a gas turbine, usually diesel, as the base load plant. Among the exceptions to this are the Canadian DDH and the British Type 42 DD and Type 21 frigate, all of which utilize COGOG plants, all with aircraft derivative gas turbines. The first DDH is scheduled for sea trials in mid 1971 and the Type 42 destroyer and Type 21 frigate are also new construction ships, none of which has yet been delivered. The other notable exception to the above is the U.S. Navy's Spruance class destroyers which are not going to be a combined plant but will instead be powered by four 20,000 horsepower G.E. LM 2500 aircraft derivative gas turbines. This installation is notable for several reasons. It is the first non-combined type plant in a destroyer/frigate type vessel outside of the USSR and beyond that, it represents the U.S. Navy's first warship installation of propulsion gas turbines in other than patrol boats or unconventional craft. The first Spruance class des-

troyer is scheduled for delivery in about two to three years.

Many of patrol/gunboat installations are either CODOG or CODAG. Several countries have very similar boats in service. One such installation consists of a CODOG plant utilizing three aircraft derivative Rolls-Royce Proteus gas turbines in a 110-115 ton boat with top speed of 54 knots. This boat is operated by about five different countries (3). The other most frequent type of installation (excluding the USSR) in patrol boats is an all gas turbine plant also utilizing three Proteus gas turbines. The British Brave class patrol boats and the Swedish T-121 Torpedo boats are of this type. The USSR has about fifty 150 ton patrol boats with all gas turbine propulsion of 5000 hp each.

There are a few significant commercial ship applications. One of the most interesting of these is in the GTS Adm. William M. Callaghan which is a roll on/roll off type ship owned by the Military Sealift Command (formerly the Military Sea Transportation Service) of the U.S.Navy. There is some difference of opinion as to whether this should be classified as a commercial ship or not since it was designed and built to provide operating experience in the design of Navy ships powered by gas turbines (10). However, it has operated since its delivery in December, 1967 as a military cargo carrier between the East coast, USA and Bremerhaven, Germany, so it is at least a merchant type ship. The main propulsion system of the ship consists of two gas turbines (originally FT4A-2s, more recently one LM 2500

and one FT4A-2), each driving a fixed pitch propeller through a reversing reduction gear. The ship has operated on marine diesel fuel most of the time with some experimental use of a heavy distillate type fuel. It is claimed that operation has been simple and maintenance has been minimal with the ship maintaining a high degree of utilization (10). A more complete description of the Callaghan is given in Appendix A.

The second interesting commercial marine gas turbine application is in the four 23,000 ton dead weight twin-screw container ships being built by the Emden, Germany yard of Rheinstal Nordseewerke for the Scarsdale Shipping Company of London to be chartered by Seatrain Lines, Inc. These ships are powered by two Pratt & Whitney 30,000 hp FT4A-12 aircraft derivative gas turbines, each driving a Lips N.V. controllable pitch propeller through locked train reduction gearing (11). These ships are expected to use a heavy distillate fuel and it is expected that the high availability and reduced manning will overcome the higher fuel costs (12). The first of these ships, the Euroliner, was launched in October 1970.

Another interesting marine gas turbine application is the recently announced decision of Broken Hill Proprietary Company Ltd. (BHP) of Australia to install General Electric heavy duty 17,500 hp MS 5212R two shaft regenerative gas turbines in two single-screw roll on/roll off special steel products-carriers. The fuel proposed is a waxy residue fuel indigenous to Australia with the same cost as Bunker "C" (13). It is not clear as to →

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out of place.

jet engine suitably marinized to serve as the gas generator and for a special power turbine to be designed to convert the energy of the hot, pressurized gas to mechanical energy. In some cases, however, the basic aero engine already has a power turbine as for driving a propeller in a turbo prop engine or for driving the fan in a high bypass ratio fan jet engine. In these cases, it is then usually not necessary to design a new power turbine. In most cases the power turbine is designed to stay in the ship with only the gas generator section being repaired by replacement; however, particularly in lower horsepower engines, the power turbine may be removed along with the gas generator.

It is usual to retain the basic aero engine lubrication system for the gas generator. This system uses a low viscosity synthetic oil which is required for the lubrication of the antifriction journal and thrust bearings used. In the case of integral power turbines also running on ball and roller bearings, the lubrication system of the power turbine is combined with that of the gas generator. Where the power turbine is designed to remain on the ship and runs on large plain bearings with thrust bearings of the Michell type, it is usual to integrate its lubrication system with that of the reduction gears. The synthetic oil used in the gas generator lubrication system will react with water under certain conditions to produce certain undesirable acidic constituents which would result in corrosion; therefore, water contamination of this oil must be avoided. (14). That is the reason the gas generator lube oil is normally cooled

whether a fuel treatment system will be required or not. This will mark the first commercial use of a heavy duty gas turbine in marine use (outside the USSR) since the John Sergeant was withdrawn from service. A GE MS 5002 series gas turbine similar to the one to be used in this application is described in greater detail in Appendix B. The first of these two ships is scheduled to be delivered in September 1972 with the second to follow a few months later.

Besides the description of the GTS Adm. William M. Callaghan mentioned above, several other marine gas turbine installations are described in Appendix A. In addition to the Callaghan, these include the Danish CODOG frigate Peder Skram, the Swedish T-121 Torpedo Boat, the Canadian DDH-280 class helicopter destroyer, and a General Electric Integrated Gas Turbine Power Plant Design done for the U.S. Maritime Administration, and, although never built, is probably representative of the type of installation that will be in BHP's roll on/roll off ships mentioned above.

2.2. Gas Turbine Engines

As has been stated previously, there are essentially two rather different types of gas turbines in marine propulsion use; the aircraft derivative type and the industrial or heavy duty type.

The aircraft derivative gas turbine is usually high pressure ratio simple cycle gas turbine which consists of a gas generator and a free power turbine. It is usual for the aero

return to p 24 now

by utilizing either the gear box mineral oil or the gas turbine fuel as a cooling medium.

Some of the marinization features that must be arranged for the aero engine to make it acceptable for marine use are as follows (15):

1) All magnesium alloys must be eliminated; usually to be replaced by a suitable aluminum alloy.
2) Compressor blading, both for stators and rotors, should be in stainless steel or titanium.
3) The thrust bearing capacities must usually be increased because of the increased thrust load in marine application.
4) The combustion equipment usually requires some redesign in order to burn a heavier distillate fuel and to achieve smoke free combustion.
5) Normally the maximum turbine inlet temperature allowed is appreciably lower than that allowed in aircraft service.
6) The usual method for reducing the corrosion of the turbine blading is to use a protective aluminum diffusion coating.

The aircraft derivative engines use distillate fuels.

The heavy duty or industrial gas turbine is usually a low pressure ratio, often regenerative cycle gas turbine. It is

not specifically designed for low weight and volume, but instead for long life requirements. The heavy duty turbine design parallels that of the steam turbine in many respects. (16). Casings are split on the horizontal center line allowing rotor removal and bearing inspections on site. The larger parts of the heavy duty turbine, as compared to the aircraft derivative, are designed to be repairable by local crews. The overall design of the heavy duty turbine is more conservative, the pressure rise per stage in the compressor is less, the combustor is made large with low heat release and the bearings are long life pressure lubricated sleeve bearings. The allowable turbine inlet temperature is usually less than aircraft types designed at the same time. The industrial type with its large combustor is usually designed to be able to burn properly treated residual fuels. In general then, the aircraft derivative turbine will have a lower specific weight and volume but will have a shorter time between overhauls and probably will not be able to utilize the range of fuel types that the heavy duty turbine will.

The heavy duty turbine also must be modified to some degree for marine service. General Electric marinization consists primarily of some material changes and coating of other materials. (17).

A tabulation of the characteristics of most of the gas turbine engines currently in use or offered for marine use is given in Table 2.2. It will be noticed from this tabulation that for gas turbine engines, it is usual to give different power ratings

TABLE 2.2 Characteristics of Current Marine Gas Turbine Engines

Turbine	Manuf.	Max Cont Power hp	Normal Power hp	TIT Max. pwr F	SFC lb/hphr Max pwr	SFC lb/hphr Norm. pwr	Spec. Pwr. at max pwr hp/lb/sec	PR
G6	AEI	8,600	8,600	1460	.65	.65	79	6.3
Olympus TM1A	RR	24,000	19,000	1620	.50	.53	105	10.3
Olympus TM3B	RR	27,200	21,000	1685	.49	.52	119	10.3
Proteus	RR	4,250	3,600	1595	.59	.63	93	7.3
Tyne	RR	4,250	4,250	1610	.49	.49	101	11.5
FT4A-2	P&W	25,500	21,500	1650	.50	.52	111	12.0
FT4A-12	P&W	28,000	24,400	1700	.51	.52	122	12.0
IM1500	GE	14,000	12,500	1650	.56	.58	95	12.0
IM2500	GE	25,500	22,200	2150	.39	.41	199	16.8
MS5272R	GE	27,800	27,800	1700	.44	.44	112	8.2
W.41	W	4,380	3,700	1450	.66	.72	83	5.0
TF 35	Avco	3,150	2,500	-	.55	.59	-	8.0
GTU 20	LMZ	6,500	6,500	1382	.51	.51	42	9.0
FT12A-3	P&W	3,200	2,500	1525	.73	.79	74	6.5

Note: Inlet temps.- LM1500,LM2500 at 100F;P&W engines and TF35 at 80F;MS5272R at 70F; all others at 60F. LM1500,LM2500 have 4"(6")H_2O inlet(exit) losses; others none.

TABLE 2.2 (continued)

Turbine	Power turbine Type	# stages	RPM	Comp. turbine Type	# stages	Compressor Type	# stages	Dimensions Weight lb	L in	W in	H in
G6	A	2	4900	A	2	A	13	45,000	260	79	86
Olympus TM1A	A	1	5660	A	1-1	A	5-7	13,000	260	126	117
Olympus TM3B	A	1	5660	A	1-1	A	5-7	13,000	260	126	117
Proteus	A	2	11600	A	2	A-C	12-1	3,200	100	40	40
Tyne	A	2	13000	A	1-1	A	6-9	2,800	104	42	42
FT4A-2	A	2	3600	A	2-1	A	8-7	14,200	312	77	86
FT4A-12	A	2	3600	A	2-1	A	8-7	14,200	312	77	86
IM1500	A	1	5500	A	3	A	17	7,500	224	84	96
LM2500	A	6	3600	A	2	A	16	10,500	267	84	84
MS5272R	A	1	4670	A	1	A	16	380,000	503	240	433
W.41	A	4	8500	-	-	A	14	18,500	138	68	65
TF 35	A	2	14500	A	2	A-C	7-1	1,050	49	30	36
GTU 20	A	2	4780	A	2	A	6-12	206,000	338	200	446
FT12A-3	A	2	9000	A	2	A	9	1,010	99	33	37

Note: All engines are simple cycle except for the regenerative cycle MS5272R and GTU 20.

such as maximum, normal, etc. The basic difference in these ratings is the difference in turbine inlet temperature and therefore the expected time between overhauls. At the lower power levels the turbine inlet temperature is lower thereby extending the life of the hot sections of the engines. This is usually arranged for aircraft derivative engines, however, sometimes industrial engines are also derated for marine use as for the Westinghouse W.41 engine used in the Canadian Coast Guard icebreaker, Norman McLeod Rogers. It has an industrial service turbine inlet temperature of 1450° F, but in the icebreaker application, a TIT of only 1350° F was used. (18).

Also, an examination of the table shows that gas turbine engine ratings tend to be given for several different compressor inlet temperatures. Aircraft engines are normally rated at 59° F while the U.S. Navy requires its propulsion gas turbines to be rated at 100° F (57) and other ratings are likely to be given at temperatures inbetween. Figure 2.1 gives an example (FT4A-12) of how the power ratings vary with inlet temperature. (19).

The other condition that should be specified in a power rating is the inlet and exhaust pressure drops. For shipboard installations it is usual to specify allowable pressure drops in the inlet and exhaust ducting on the order of 3-4" H_2O for the inlet and 5-6" H_2O for the exhaust. Since these pressure drops will have a significant effect on the performance of the engine, they should be specified in a power rating. If no exit

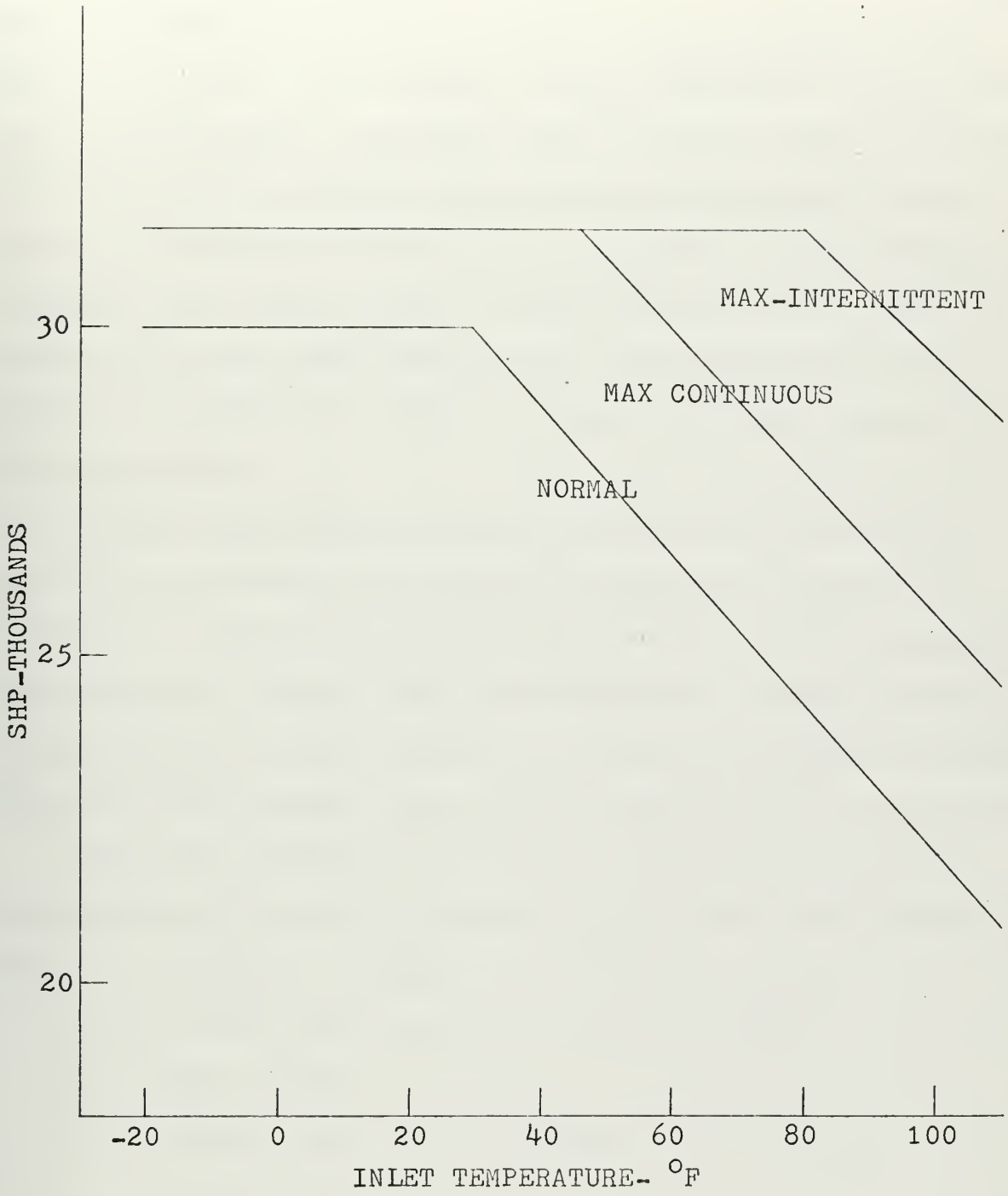

FIG. 2.1 Variation of Pratt & Whitney FT4A-12 Power Rating with Compressor Inlet Temperature (19).

1. Inlet pressure is 14.7 psia.
2. No inlet or exhaust duct pressure losses.

and inlet pressure drops are stated, it is normally assumed that there were none. As an example of how significant these pressure losses can be, a pressure loss of one per cent in the intake ducting of a marine Olympus engine would cause a power loss of 2.2% and an increase of one per cent in the exhaust back pressure would cause a loss in power of 1.2%. (20). This indicates that in a ship installation particular care must be given to the design of inlet and exhaust ducting to minimize pressure losses.

Another point which can be illustrated by the table is that it is customary, particularly for aircraft derivative engines, to continually uprate the same basic engine design by increasing the turbine inlet temperature as improved coatings and/or materials become available. Compare the FT4A-2 and the FT4A-12 or the Olympus TMIA and the Olympus TM3B, for example.

From this tabulation of engines, one can also see the significant differences in the LM 2500 and the other aircraft derivative engines. Among these differences are:

1) TIT over 400° F greater than any of the other engines.
2) Pressure ratio of 17:1 versus 12:1 or less for the others.
3) SFC of .39 lb/hp hr versus .49 or greater for the other simple cycle engines.
4) Specific Power of 199 hp-sec/lb com-

pared to 122 or less for the others.

5) Considerably lower in specific weight and volume than any of the others.

To achieve the high TIT, the LM 2500 makes extensive use of film, inpingement and convection cooling of both stator and rotor blades in both stages of the high pressure turbine. (21). (A more complete description of the LM 2500 is given in Appendix B). The LM 2500 is often termed a second generation aircraft derivative engine because the aircraft engine (TF 39) that it was developed from went into service several years after most of the other aircraft derivative parent engines.

The one big intangible that can not be given in the table because it isn't known is how the reliability, as evidenced by the time between overhauls, of the LM 2500 will compare with the earlier engines.

In addition to the description of the LM 2500, Appendix B also contains descriptions of a first generation aircraft derivative turbine, the Rolls-Royce Olympus TM1 and of a relatively recent General Electric heavy duty design, the MS 5272R. The MS 5272R is representative of GE heavy duty marine gas turbines which are available in power ranges from 3500 to 4500 HP and from 7500 to 60000+ HP(17).

2.3. Areas of Special Interest in Marine Applications

There are several aspects of marine gas turbine propulsion applications that are of particular interest. Among these are thermal efficiency and specific powers of the gas turbine engines, the method of providing reversing thrust, the effects of the sea environment on the gas turbines, and the types of fuels required by the engines.

2.3.1. Thermal Efficiency and Specific Power Considerations

The overall thermal efficiency of a gas turbine plant is affected by several variables. Among these are compressor inlet temperature, turbine inlet temperature, compressor pressure ratio, pressure losses in the various components and in inlet and outlet ducting, amount of cooling air required for turbine, whether the plant is a simple cycle or regenerative cycle and if cycle complexities such as intercoolers or reheaters are used.

For the ideal simple Brayton cycle (prototype cycle for the simple cycle gas turbine) it can be easily shown that the thermal efficiency (assuming a perfect gas) is given by (22):

$$\eta = 1 - \frac{1}{r^{(\frac{\gamma-1}{\gamma})}}$$

where γ is the ratio of specific heats
and r is the pressure ratio

This indicates that the thermal efficiency is independent of the turbine inlet temperature for the ideal cycle. However, for real gas turbine cycles, the thermal efficiency is related

very closely to the turbine inlet temperature as well as to the pressure ratio. This is primarily true because the thermal efficiency of the gas turbine is greatly effected by the component efficiencies of the compressor and the turbine because the compression work is a large percentage of the turbine work, so small relative variation in these efficiencies can greatly effect the output. For each turbine inlet temperature there will be an optimum pressure ratio for thermal efficiency. This optimum will vary somewhat depending upon component efficiencies, losses, cooling requirements, etc.

When the regenerative Brayton cycle is considered, it is found that the thermal efficiency is a function of the turbine inlet temperature as well as the pressure ratio even for the theoretical cycle (22). This is also true in real cycles.

Specific power for a gas turbine is defined as the horsepower output divided by the air flow rate and is therefore proportional to work output of the engine per pound of air. The specific power is an important parameter for at least two reasons:

1) Higher specific power means lower air flow for a given power which usually means a smaller engine with higher specific weight and volume.
2) Also, for a marine gas turbine in particular, the lower air flow means less inlet and exit ducting pressure loss and arrangement problems.

The specific power is also a function of most of the same var-

iables as the thermal efficiency but it does not vary with them in the same manner as does the efficiency. For this reason, even though for a given turbine inlet temperature there will be an optimum pressure ratio for maximum specific power, this in general will not be the same as for maximum thermal efficiency.

Before considering the overall thermal efficiencies and specific powers presently attainable by gas turbine engines, it is well to consider the present state of component efficiencies.

Polytropic efficiencies (discussed in Appendix C) are normally used in discussing the state of the art of compressor or turbine design. Compressor efficiencies (polytropic) currently average approximately 90% in aircraft design (23) and perhaps slightly higher in industrial design where pressure rise per stage is not as important. Because of the high pressure ratios used in aircraft engines, there is great incentive to design for higher average stage pressure ratio. Current aircraft compressor designs have average stage pressure ratios of about 1.29, whereas their industrial counterparts develop an average stage pressure ratio of about 1.12. Most current aircraft research effort is currently directed at further increasing this average stage pressure ratio without sacrificing efficiency (23).

Another difficulty in going to higher pressure ratios in a compressor is that the higher the pressure ratio for which the compressor is designed, the narrower will be the range of stall-

free operation (24). At low speed, the first stages of the compressor tend to stall first and above design speed the last stages. Generally, there are three methods used to prevent stall, particularly at low speeds during starting. All three involve some kind of decoupling of the first stage from the last. The simplest is to bleed off air at an intermediate stage. Another way is to divide the compressor and its driving turbine into two parts so that the RPM of the two parts can vary independently; several engines use this arrangement. The last method currently used is to employ a means of varying the angle of the stator blades in the first few stages of the compressor. The LM 2500 has variable stator blades in the first six stages of its 16 stage axial compressor.

Current turbine polytropic efficiencies appear to be at least as high as the 90% efficiency of compressors and probably slightly higher. Most turbine development thrust is in attempting to develop new higher temperature blade materials and in improving blade cooling methods in order to allow higher turbine inlet temperatures.. Current allowable TIT's with uncooled blades are in about 1700° F range. (23, 24). This temperature has increased at about 20° F per year for the past several years. Some of the current aircraft engines with aircooled nozzle vanes and rotor blades have turbine inlet temperatures of about 2300° F, GE CF6-6 has TIT of 2300° F, GE TF 39 has TIT of 2300° F and Rolls-Royce RB211 has TIT of 2270° F (8). In marine use, aircraft engine TIT's are normally reduced as part of the

marinization to achieve more acceptable time between overhauls. For instance, the LM 2500 which has a TIT of 2150° F is derived from the TF 39 which has a TIT of 2300° F. In marine use, the LM 2500's TIT of 2150° F is several hundred degrees higher than any other engine currently in use. Most of the other engine TIT's range from approximately 1700° F downward as is shown in Table 2.2. As was noted earlier, the effect of the LM 2500's high TIT on its reliability is still a question mark.

Combustion efficiencies approach 100% currently.(23). Aircraft-derivative engine combustion system problems primarily are concerned with the effects of the heavier distillate fuels with their higher luminosity, higher viscosity and relatively poorer volatility. Industrial gas turbine engine combustors may have to be redesigned to provide better cooling methods as higher temperatures are sought.(23).

In regenerative gas turbines thermal effectiveness of the regenerator is an important parameter. The regenerator is a heat exchanger which utilizes the hot turbine exhaust to heat the air out of the compressor prior to its introduction into the combustion chamber. The thermal effectiveness is the ratio of the heat actually transferred in the heat exchanger to that possible to transfer if the exit temperature of the lower capacity rate (product of mass flow rate and specific heat) stream reached the inlet temperature of the other stream, i.e. in an infinitely large heat exchanger. In general, as the thermal effectiveness of the regenerator is increased, the cycle

thermal efficiency is increased, but the weight and size of the regenerator also increases with effectiveness. General Electric recommends a thermal effectiveness of about 80% for its marine gas turbines. (17). This can result in the regenerator being quite large. In the 20,000 hp GE regenerative plant described in Appendix A, the thermal effectiveness is 77.3% and the regenerator weight is 112.4 tons with approximate overall dimensions of 12.5 ft. X 12.5 ft. X 15 ft.

Returning to the consideration of present marine gas turbines overall thermal efficiencies; instead of the thermal efficiency, the specific fuel consumption (SFC) is often stated. This is equivalent to giving the thermal efficiency if the lower heating value (LHV) of the fuel is known since:

$$\eta = \frac{2545}{SFC \times LHV}$$

where SFC is in lb/hp-hr

and LHV is in Btu/lbs

LHV's for distillate fuels are about 18,400 Btu/lbs and for residual fuel oils are about 17,500 Btu/lbs, so thermal efficiencies can be readily estimated from SFC's and vice versa if the type of fuel is known.

The SFC's, as well as the specific power, for most current marine gas turbine engines is given in Table 2.2. The LM 2500 can be seen to be considerably better both in fuel consumption and specific power as would be expected from its high turbine inlet temperature. In terms of thermal efficiencies, the range

is from about 35% for the LM 2500 downward to about 21.3% for the AEI 66 with its relatively low TIT and to about 19% for the Pratt & Whitney FT 12A-3, a comparatively low power first generation aero derivative engine.

2.3.2. Method of Thrust Reversal

Many methods of providing thrust reversal have been proposed, among the most feasible of these schemes are:

1) using electrical transmission system
2) using controllable, reversible pitch propellers
3) using a hydraulic coupling with reversing capability
4) using a reversing reduction gear with friction clutches
5) using a reversing gas turbine.

The most common method, presently in service, is by the use of controllable reversible pitch propellers (CRPP's). These propellers are ones in which the blades are separately mounted on the hub, each on an axis and in which the pitch of the blades can be changed, and even reversed, while the propeller is running, by means of an internal mechanism in the hub. The usual mechanism for changing pitch consists essentially of hydraulic pistons in the hub acting on crossheads. The controllable-pitch propeller can be made almost as efficient as the solid, fixed-blade propeller at any particular chosen condition, the only difference being in the larger hub

needed to house the pitch-changing mechanism. (26). However, when the pitch is changed all sections turn through the same angle, so that the pitch face is no longer a true helical surface.

The earliest use of hydraulic activated CRPP's is believed to have been in the period of 1934-1937. (72). Escher Wyss of Ravenburg, Germany and Karlstods Mehaniska Werstad (KaMeWa) of Karlstad, Sweden, both of whom are currently among the leading manufacturers of CRPP's, both started in this time period. Other leading manufacturers of CRPP's include Lips N.V. and Liaaen. In the United States, besides licensees of the aforementioned companies, Baldwin Lima Hamilton (BLH) in conjunction with the U.S. Navy has designed and built several CRPP's.

Currently, it is believed that the highest individual horsepower CRPP's in service are about 22,000 horsepower in naval ships and about 26,000 horsepower in merchant ships. (3, 27). In the very near future, however, 30,000 hp LIP's N.V. propellers will be in service on both the Euroliner and Canadian DDH.

The use of an electrical transmission system is certainly feasible and has been used in several applications including the GTS Auris and the Canadian Coast Guard icebreaker. It is generally not used, however, because of relatively poor transmission efficiency, high weight and volume, and high first cost. (28).

The GTS Auris also used hydraulic reversing which was deemed to be very effective although problems were experienced

with the friction clutches used. Some of the British COSAG plants utilize hydraulic couplings (29) and other applications have been recently proposed. (30).

The reversing gear installation in the GTS Callaghan (described in Appendix A) seems to have shown the reliability and feasibility of this method, at least up to the power level of 20,000 hp.

At first glance the use of a reversing gas turbine might appear to be both the most obvious and the most desirable since marine steam turbine installations normally have a reversing turbine section and marine diesels are normally of the reversing type; however, it would add considerable complexity to the design of the gas turbine and require extensive development effort. This has not yet been attempted because most non-marine gas turbine applications do not require this reversing capability and the degree of usage in the marine field has not warranted the development expenditure. Some development work is proposed on an axial reversing turbine by General Electric in conjunction with Marad, (28); while Rolls-Royce (Bristol Siddely Division) has considered a radial reversing turbine in a study for the British navy. (20, 31). The work on the radial turbine has been suspended primarily due to the large size of the turbine volute required and also because acceptance of CRPP's removed some of the incentive. (32). As far as is known, the GE development is continuing.

2.3.3. Effects of the Sea Environment

In both the discussion of gas turbine engines and of ship installations, mention has been made of specific marinization procedures for the engines and sea salt separators in the inlet air ducting as steps required by the ocean environment. The salt water in the intake air can effect the engine in several ways. It will cause fouling of the compressor blades resulting in lowered efficiency and reduced power output so that even with separators, provision must be made for compressor cleaning. This is usually accomplished by water washing with periodic cleaning with a solid material such as carbo-blast. (33). The salt water will also corrode the compressor blading but this can usually be prevented by using the proper blade material, such as titanium. Undoubtedly, the most severe problem assoc-iated with salt water in the engine air is the corrosion of the hot section of the engine. At temperatures above about 1550° F the sulfur in the fuel combines with the salt in the air to form an extremely corrosive molten slag. This sodium sulfate accelerated oxidation is generally termed sulfidation. Although the exact mechanism of the sulfidation is not completely known, there is general agreement that reduction of sulfur content in the fuel will not prevent it; it was calculated that minimal amounts of sulfur in the fuel provide more than enough sulfur to react with the sodium chloride in the air. (34). There is also evidence to suggest that carbon will accelerate the sul-fidation possibly by creating momentarily the necessary reducing

conditions to penetrate the protective metal oxide film and initiate sulfidation. (32). Another feature of this problem is that above 1900° F the corrosion is less, indicating that the slag has probably vaporized and only normal oxidation is occurring. (35). The general approach to coping with this problem is as follows:

1) Removal of as much salt as possible from the inlet air by using separators such as 90 degree duct turns, louvers or turning vanes in the inlet ducting. It appears that sea salt particles over 5 microns will be separated by these types of separators and that the concentration of particles below 5 microns probably will not exceed 0.05 ppm even at highest wind velocity. (36). Demistors or knitted mesh made of stainless steel or polypropylene have also been used successfully at low air velocities to remove the salt. (32, 33).
2) Development of more corrosion resistant materials and coatings for nozzle vanes and blades. Addition of chromium to the blade alloys has been found beneficial and aluminum diffusion coatings have helped considerably. (35).
3) Design of carbon reducing fuel nozzles and smoke reducing burner cans. (37).

Also the reduction of metal temperature through the use of cooled blades and nozzles is helpful. Plus the clean cooling air film provided in the LM 2500 should help to shield the metal from the corrosive gases. (21).

Another problem associated with the salt water environment is the contamination of the fuel by the salt water. This water can normally be removed by a purification system utilizing coalescent filters.

2.3.4. Gas Trubine Fuel Requirements

As gas turbine engines have evolved in two different directions, so have the fuels required by them. Aircraft gas turbines have been designed as light weight, high performance machines requiring high-grade fuels while industrial or heavy duty gas turbines are normally designed for a wide range of fuel types. Aircraft fuels have properties which have been selected and compromised to provide long time storage characteristics suitable for pumping, filtration, metering and atomization at high altitudes and low ambient temperatures and good combustion characteristics. These fuels, primarily JP4 and JP5, are distillates differing from commercial diesel or burner fuels by having lower freezing points, higher aromatic content, and specified luminosity characteristics. Fuels for the industrial turbines are selected largely by economics. These fuels are required to be inexpensive and are generally impure. In order of importance, the most common are natural

gas, petroleum distillates, refinery and chemical plant gases and liquids, and residual fuel oil. (38).

ASTM has recently adopted specifications for gas turbine fuels which classify the fuels by four grades and are intended to cover the requirements for fuel oils suitable for use in gas turbines excepting gas turbines actually used in aircraft. Table 2.3 summarizes the ASTM specifications plus presents some commercial and military fuels falling into the various grades. (38, 76). Most aircraft derivative marine gas turbine installations to date have utilized either JP5 or marine diesel. However, as mentioned above, the GTS Adm. William M. Callaghan has attempted some use of a heavier distillate fuel and intends to continue and it is intended that the container ship Euroliner will use a heavy distillate when in service.

In adapting an aircraft gas turbine to industrial or marine use, it appears that it might be necessary to specify a minimum luminometer number for the fuel (indicative of radiation from the flame, low luminometer number high radiation) in order to assure satisfactory life of the combustion chamber since aircraft fuels normally have low radiation characteristics. (38). However, other authorities feel this is generally not necessary. (20). Other combustion problems encountered in using heavy distillates in aircraft derivative turbines include ignition problems, poor combustion efficiency, smoke output and burner carboning. (39). The U.S. Navy has run tests on a Pratt & Whitney FT4A aircraft derivative gas turbine util-

TABLE 2.3 Types of Gas Turbine Fuels (38,76)

ASTM Designation	Description	Max. Vanadium	Max. Na+K	Fuel Types
No. 1 - GT	Volatile distillate of 550 F max. 90% distillation temp.	2 ppm	5 ppm	JP-4 JP-5 Kerosine
No. 2 - GT	Medium volatility distillate of low ash with 540 F min. and 675 F max. 90% distillation temp.	2 ppm	5 ppm	Marine Diesel
No. 3 - GT	Low volatility, low ash fuel which may contain some residual components.	2 ppm (a)	5 ppm (a)	NSFO
No. 4 - GT	Low volatility fuel containing residual components. Has higher vanadium content than No. 3 - GT.	500 ppm	10 ppm (b)	

(a) For gas turbines operating below 1200 F maximum gas temperature, the limitations on vanadium and sodium plus potassium may be waived provided that a silicon base additive or equivalent is employed.

(b) Where water washing facilities are available at the point of use these requirements may be waived by mutual agreement between the purchaser and seller.

izing a heavy distillate fuel. (40, 37). In addition to the problems already stated, it was found that hot section corrosion was significantly increased. This is believed to be due to the vanadium (0.5 to 1.5 ppm) in the fuel. It is felt that more recently developed coatings and materials can reduce this corrosion to an acceptable level for these small concentrations of vanadium.

The burning of residual fuel oils in gas turbines has been limited to heavy duty type gas turbines. The biggest problem involved in burning a residual fuel in a gas turbine has been the fuel oil ash deposition on turbine blading causing deterioration in performance and most importantly severe corrosion of the blading. The principal impurities that are normally in residual fuel oils which contribute to the ash formation are sodium and vanadium. These elements form compounds during combustion (sodium vanadates, vanadium pentoxides) which are semi-molten and corrosive at temperatures as low as 1150° F. Since all modern gas turbines operate at higher turbine inlet temperatures than 1150° F, these elements must be removed or somehow prevented from forming the molten ash.

The interest in the development of a method for burning residual fuel in gas turbines is not too high among manufacturers at this time. The number of manufacturers actively concerned in the development of such units has fallen from a peak of more than twenty in 1955 to probably less than five at the present time. (41). In the United States, General Electric

Heavy Duty Gas Turbine department appears to be the manufacturer most interested in utilizing residual fuel oils in gas turbines. GE's present fuel treatment system (17) does not appear to be significantly different from that developed in 1955 (42) and used on the GTS John Sergeant. (2). The basic fuel treating method consists of a water-washing system to remove the sodium and an additive system for inhibiting the vanadium.

In the water-washing system, the fuel oil is heated and mixed with 5 to 10% water. A small amount (about .025 per cent) of emulsion breaking fluid is mixed with the oil just before introducing the water to aid in later oil and water separation. The oil and water mixture is then fed to two centrifuges in series where the water is separated from the fuel; most of the water soluble contaminants (including sodium but not vanadium) are picked up by the water and removed from the oil.

Since most of the vanadium compounds are mostly oil soluble and are not removed in the water-washing process, an additive to inhibit the corrosive effect of the vanadium is added to the fuel immediately prior to being fed to the gas turbine combustion system. Magnesium base additives (most economical considered to be magnesium sulfate) are normally used to form magnesium-vanadium compounds during combustion which melt at over 2000° F and therefore do not form a corrosive slag in present heavy duty machines which have TIT temperatures of 1700° F or less.

For a 2,000 gph fuel capacity, the fuel treatment plant is supplied as three modules each requiring a deck area of 8 feet by 12 feet and a height of 9.5 feet. Estimated weight is about 5.5 tons. (43). The system is automated except for the mixing of the magnesium sulfate brine for the additive treatment.

This method of fuel treatment appears to succeed in allowing the use of residual fuels in heavy duty gas turbine with minimal corrosion of the turbine blading at least for TIT's in the range of 1350 to 1450° F as evidenced by experience with GTS John Sergeant (2) and some land based power plants. (44, 45). It appears that the major drawbacks at this time in burning residual fuel in heavy duty marine gas turbines are the volume and weight of the fuel treatment system, the water required for washing (up to 10% of the oil flow) and the probable high first cost (38, 43) of the system.

2.3.5. Cost Considerations

In considering the costs of marine gas turbine propulsion systems, some consideration must be given to research and development costs. Research and development efforts can generally be divided into two areas, general research and development efforts without definite specific applications in mind and other more specific development for a particular application. The first type of general research and development cost is usually supported by governmental agencies and by the manufacturer himself whose added costs are reflected in higher equipment prices.

The second type of development costs are usually paid by the user for whom the specific application is being developed. In the aircraft industry this type of gas turbine engine development program can run to 50 to 200 million dollars per program. (46). Marine applications can not support this level of development costs but a certain amount of development support is available and will be discussed later. The costs for simple cycle engines range from about $15/hp to $45/hp (23, 47) and up to $75/hp for regenerative cycle engines including the regenerator. (43).

In considering the cost of marine gas turbine installations utilizing developed engines, the cost of the engines themselves is not really as significant as the propulsion plant cost and more specifically, the installed propulsion plant cost. A study by Frankel and Simpson (48) comparing diesel, gas turbine and steam propulsion plants for single screw merchant ships up to about 40,000 shp found installation costs varied considerably. The gas turbine plant, because of its relative simplicity, was found to have the lowest installation costs over the entire power range considered. The results of a more recent study by Hempel and Reulein (49) are given in Figure 2.2. Several different merchant ship types were included in this study with this being the average results; the costs of individual plants varied by about 5 per cent. The discontinuities at about 40,000 shp are due to the change-over to twin shaft plants. These total installed costs are for complete propulsion plants including

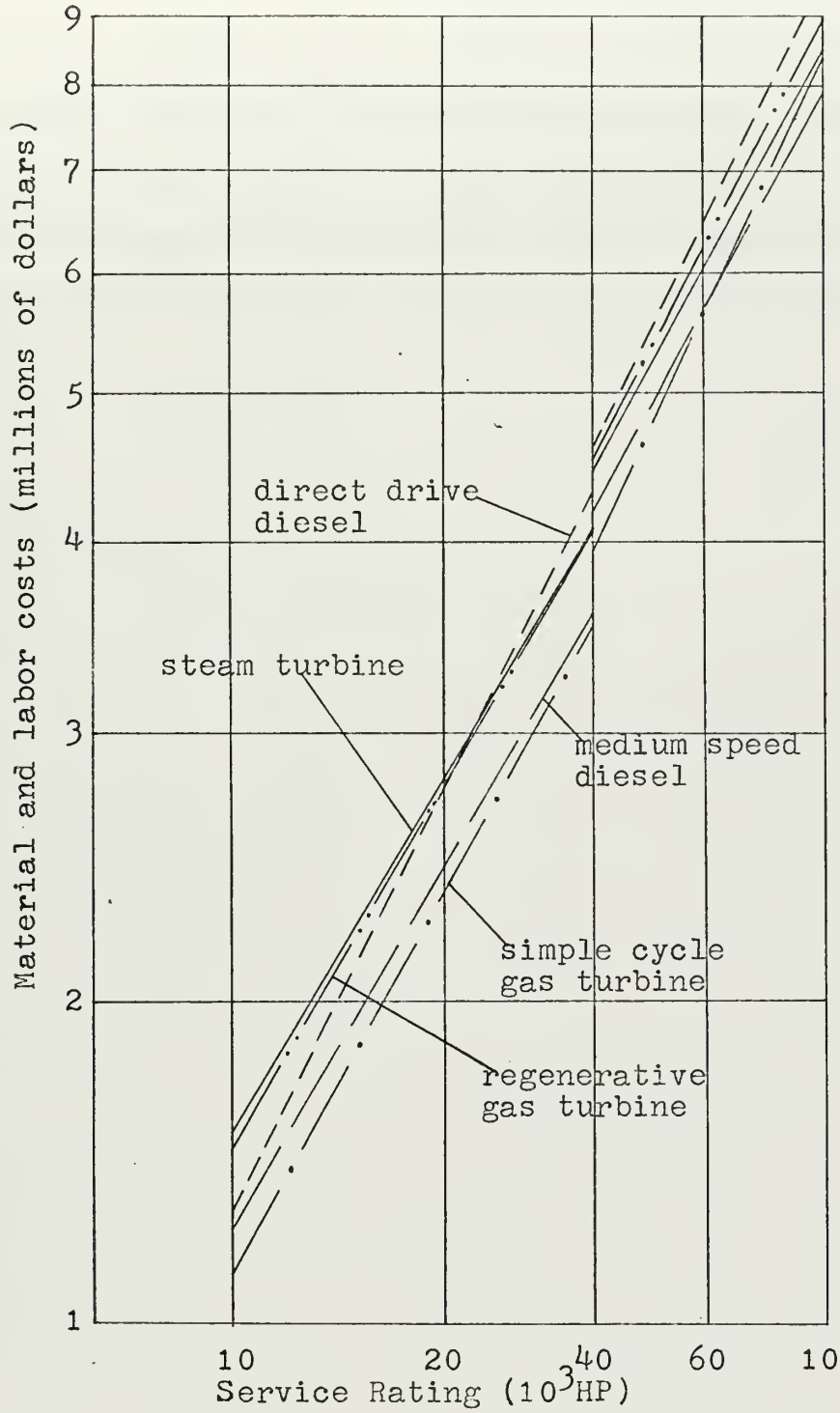

FIG. 2.2 Total Costs of Various Propulsion Plants(49) (1969)

prime mover and spare parts, gear boxes, shafting and propellers (CRPP's for gas turbine plants), intake and exhaust system steam and fresh-water treatment plants, power generator, remote control and monitoring equipment. This type of study is necessarily general and detailed studies of a specific application might show slightly different costs for the various types of plants considered.

3. FUTURE DEVELOPMENT

The future of marine gas turbine propulsion is considered by looking at the future development of the engines themselves and methods of providing reversal of thrust coupled with an examination of the suitability of these engines for different ship types. Only relatively near future applications (approximately the next decade) are considered.

3.1. Gas Turbine Engines

In considering the future development of the gas turbine engines, several areas are considered such as the individual component development, thermal efficiency and specific power obtainable through the utilization of different cycle configurations, the desirability as well as the probability of heavier fuels being able to be utilized by the gas turbine, the future reliability and maintenance requirements and other consideration, such as development support.

3.1.1. Component Development

As was stated in the previous section, compressor efficiencies (polytropic) are on the order of 90% presently and most work, particularly in aircraft engines, is devoted to developing greater pressure rise per stage while maintaining the present level of efficiency. Therefore, it is expected that no more than one to two per centage points rise in efficiency is to be

expected in the near future. At the same time it is expected that the attainable compressor pressure ratios of aircraft engines will continue to rise with perhaps 32:1 pressure ratio attainable in the next decade. (23).

Present turbine efficiencies are also in the 90% range with approximately the same level of increase expected to perhaps 92 to 93% in the future. Turbine inlet temperatures will continue to rise both from material development and better cooling techniques. At the present, there appears to be no major breakthrough on the horizon in turbine blade material development such as somehow using ceramics (24) and sulfidation continues to be a problem for marine use; however, it appears that the previous 20° F/year average increase is likely to continue. It appears that with this continued material improvement plus the development of advanced cooling techniques, advanced impingement-convection and transpiration, aircraft turbine inlet temperatures will rise to perhaps 2700 to 2800° F by 1980. (23, 24). But since aero derivative engines are commonly derated for marine use by lowering the TIT by 150 to 200° F, it appears that the highest marine gas turbine inlet temperature to be expected in the next ten years (even utilizing latest aircraft engines) is 2500 to 2650° F. Because of conservative design procedures in heavy duty turbines, the TIT's achieved by them will probably be somewhat less.

For regenerative cycles which are only practical with the lower pressure ratio cycles more common to heavy duty

turbines (this is made clear in the next section on possible cycle configurations), the continued rise in turbine inlet temperatures will present severe problems in high temperature compact heat exchanger design. In general, there are two types of regenerators used in regenerative gas turbines. One is the more usual type of heat exchanger where the hot and cold fluids are separated by a fixed wall; this type is often called a recuperator, particularly in England. The other is the periodic flow regenerator where heat is alternately exposed to the hot exhaust gases and to the cooler compressor outlet air. The most common type of periodic flow regenerators are rotary regenerators similar to Lungstrom air preheators. The advantage to be expected of the rotary regenerator is the possibility of more compact design than with the stationary type. Because of the difficulty in sealing the rotary regenerator, to separate the gas and air flow, at higher pressure levels, and the complexities (and usually accompanying lower reliabilities) in the low speed rotation of the large regenerators that would be needed for marine propulsion plants, it is considered unlikely that rotary regenerators will be used. Much work has been done in developing compact stationary heat exchanger designs for regenerators (50), but even these "compact" regenerators are quite heavy and bulky for marine propulsion power levels. These compact heat exchangers, normally with relatively thin walled plate and fin construction, experience severe thermal stresses when used with the high temperature gases which result

in reduced reliability. Also the flow passages are small, resulting in fouling problems. Because of the thermal fatigue problems, the most optimistic prediction of allowed heat exchanger entry temperature in the near future does not exceed about 1450° F (51) corresponding to approximately a 2500° F TIT at optimum (SFC) pressure ratio for a regenerative cycle. Many authorities in gas turbine and marine engineering field (46) appear to feel that TIT's in the 2300 - 2400° F range for regenerative gas turbines is somewhat optimistic and would cause serious maintenance problems. It is felt that on the basis of this, plus the fact that heavy duty turbines tend to be designed more conservatively anyhow to achieve long service life, that TIT's for regenerative gas turbines will probably not be pushed above 2400° F in the next decade.

Regenerator effectiveness values will probably lie in the 70 to 90% range with much of the development work going to try to reduce the size and weight of the heat exchangers for a given effectiveness in the present temperature ranges. (46).

3.1.2. Thermal Efficiency and Specific Power

The thermal efficiency besides being a function of the allowable turbine inlet temperature (and the cooling losses required to obtain it), the component efficiencies, various duct and combustor pressure losses, and the compressor pressure ratio is also greatly effected by the cycle configuration. The two basic open cycle configurations are the simple cycle and

the regenerative cycle each of which may be further complicated by the use of compressor intercoolers and/or turbine reheaters. In addition to these gas turbine cycles, various methods of combining gas turbine cycles with vapor turbine cycles (principally steam) have been proposed. The most common combined cycle utilizes the gas turbine exhaust in an unfired boiler to generate the vapor used in a simple Rankine cycle. The vapor turbine may be on the same shaft as the gas turbine power turbine or may be geared to it.

Several studies have been carried out to determine thermal efficiency and specific power as functions of turbine inlet temperature for the cycle configurations described above. (23, 52, 53, 54, 55, 56). These studies differ as to what cycles are chosen and as to what values for the various parameters given above are assumed. Among the more interesting results are those given by Robson, et. al. (23) for simple and regenerative cycles and combined gas turbine and steam cycles, and those given by Bindon and Carmichael (55) for combined gas turbine and vapor cycles. Some results from these studies are given in Figure 3.1 through 3.4 with principal parameter assumptions of each study given in Table 3.1.

The performance characteristics of simple cycle gas turbines with turbine inlet temperatures, pressure ratios and component efficiencies, with appropriate cooling and pressure losses, in the range of those probable in the near future are given in Figs. 3.1 (23). Some points that can be made from

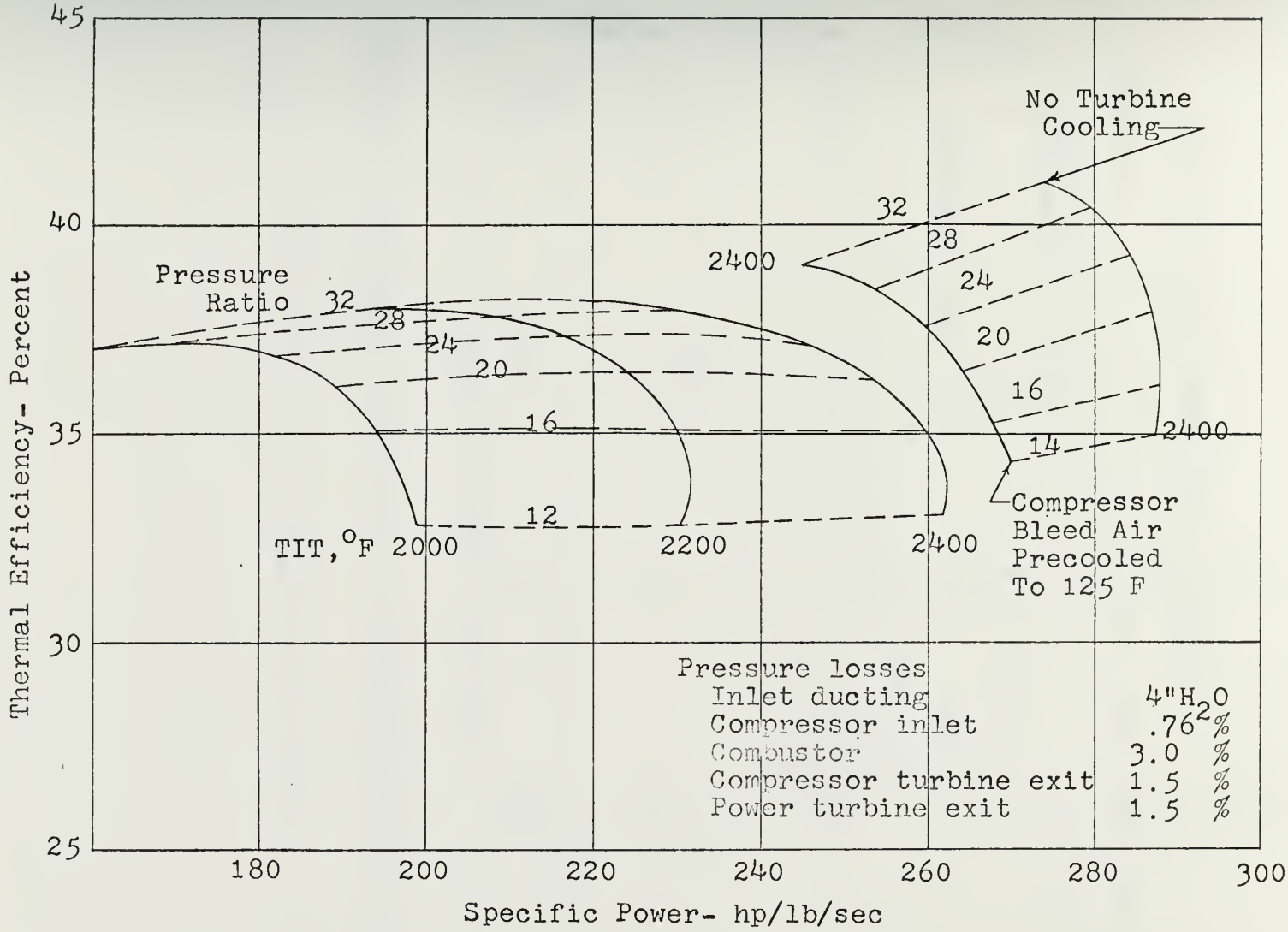

FIG. 3.1 Estimated Performance of Simple Cycle Gas Turbine (23)

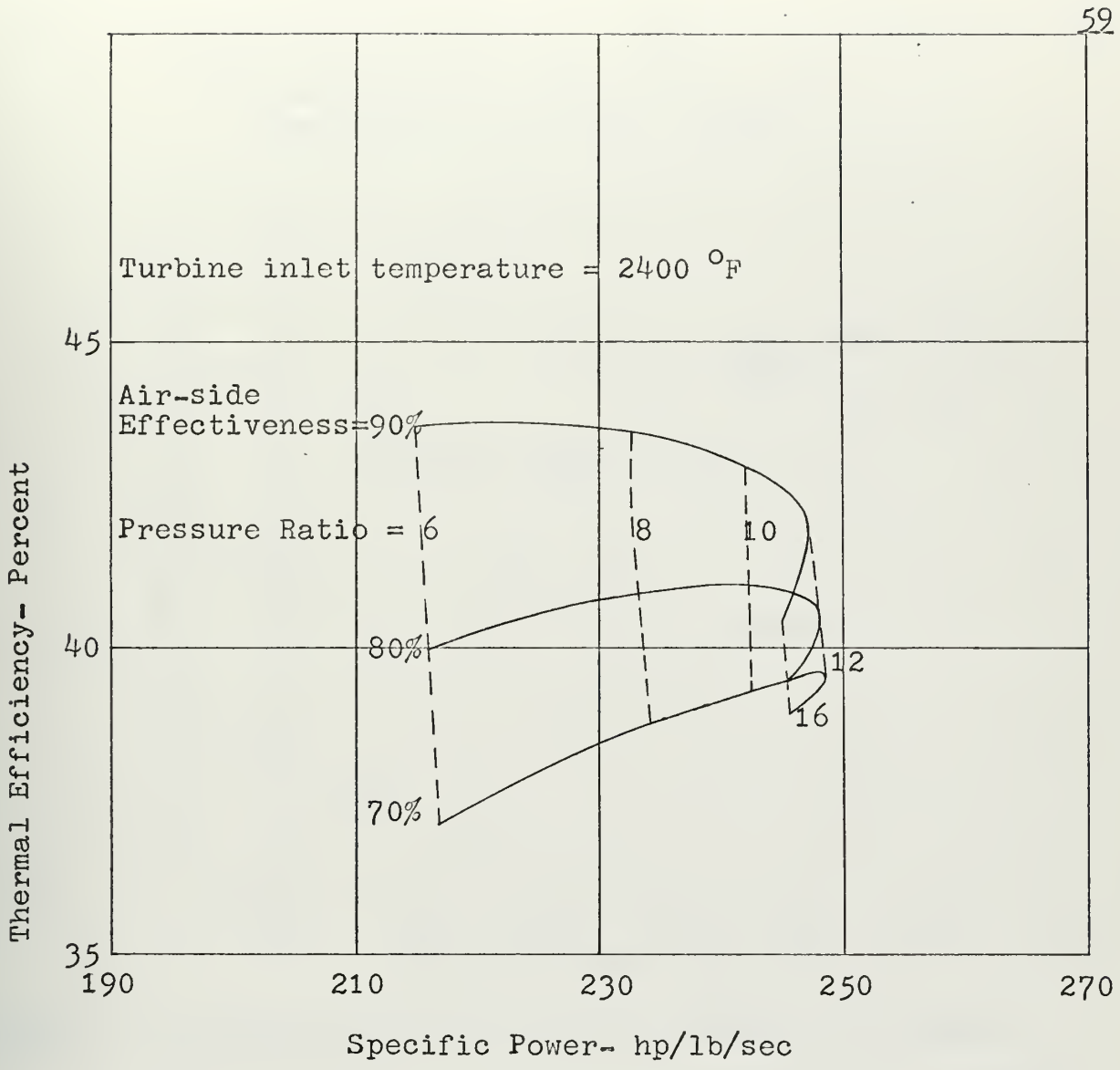

FIG. 3.2 Estimated Performance of Regenerative Cycle Gas Turbine (23)

Regenerator total pressure drop = 4%

FIG. 3.3 Estimated Performance of Combined Gas Turbine and Steam Turbine Power Plant (23)
Steam Cycle- 2400 psig/1000F/1000F
Steam Cycle Efficiency = 38.8%

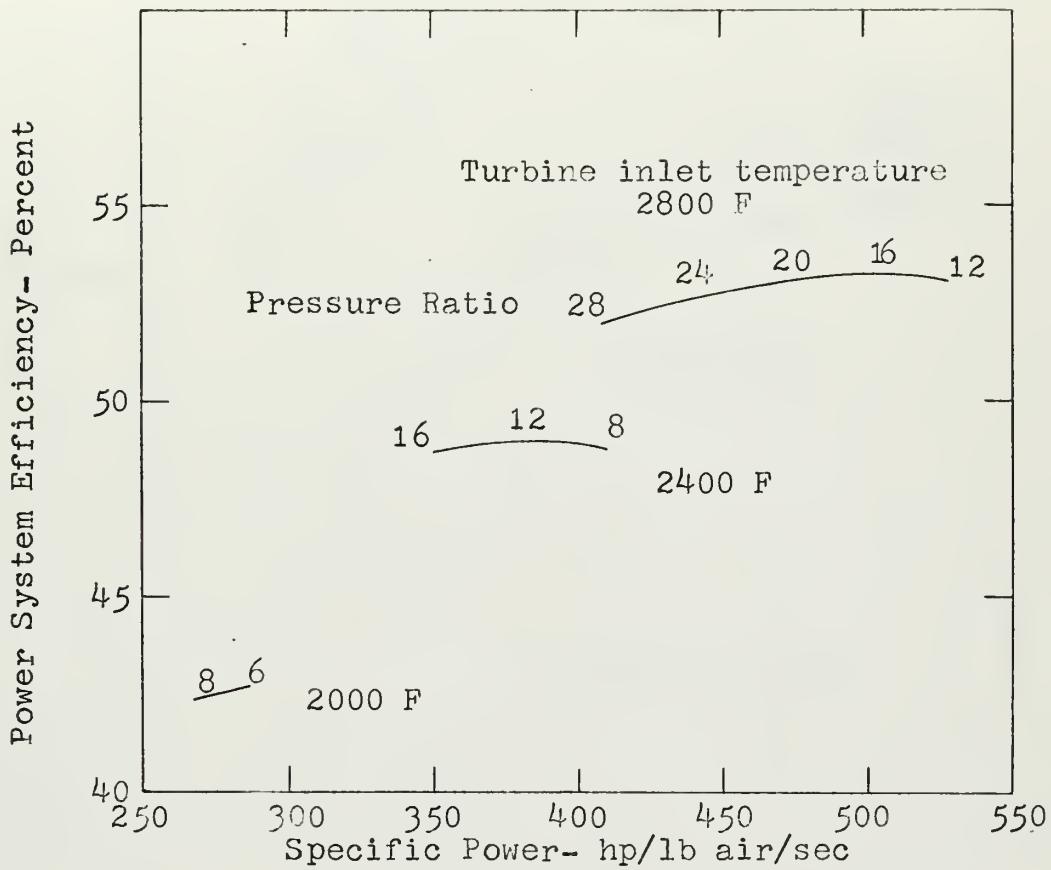

TABLE 3.1 Assumptions and Data Used in Cycle Performance Calculations.

	Bindon & Carmichael	Robson, et al
Gas Turbine Cycle		
Compressor efficiency(polytropic)	0.90	0.92
Turbine efficiency(polytropic)	0.90	0.91
Combustion efficiency	0.985	1.00
Regenerator effectiveness	0.75	varied
Total pressure losses		
Simple cycle	0.10	-
Regenerative cycle	0.15	-
Combined cycle	0.11	-
Vapor Turbine Cycle		
Turbine efficiency	0.85	-
Feed Pump efficiency	0.70	-
Condenser temperature	80 F	-
R.21 max. temperature	300 F	-

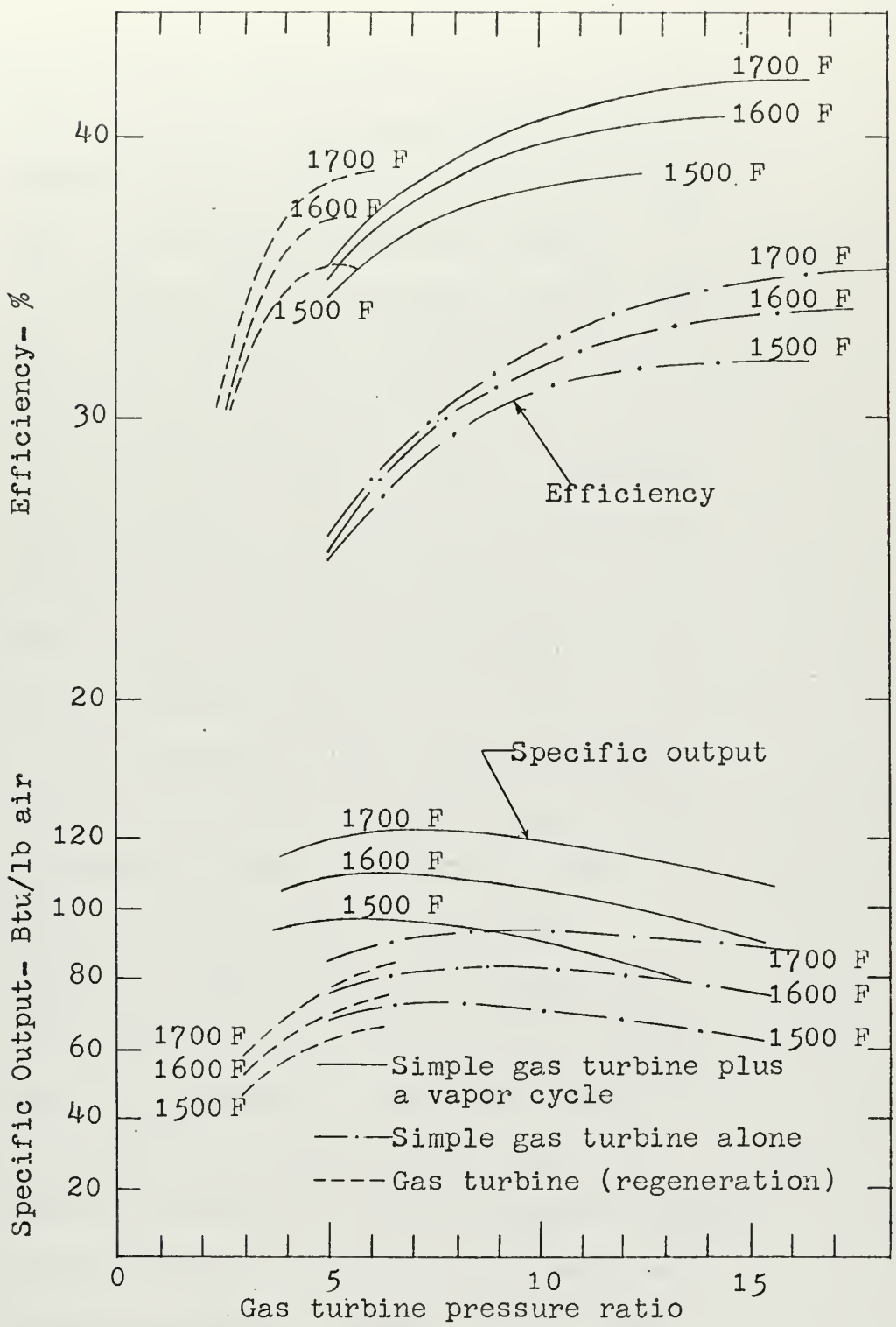

FIG. 3.4 Estimated Performance of Simple Gas Turbine, Regenerative Gas Turbine and Combined Gas Turbine and Vapor Turbine Power Plants (R.21 Vapor Turbines) (55)

examination of these results are:

1) For a given TIT, optimum pressure ratio for maximum specific power is much lower than that for maximum thermal efficiency.
2) At turbine inlet temperatures in the range under consideration, increasing TIT produces only a small rise in thermal efficiency (at optimum PR) because of cooling losses primarily; however, increasing TIT produces a very large increase in specific power (especially at the optimum PR for maximum specific power).
3) If the compressor bleed air for turbine cooling were to be cooled by some external means, a gain in efficiency and specific power could be realized.
4) Figure 3.1 also gives an indication of what could be achieved if uncooled blades could be operated at these high temperatures, but as stated before, this is highly improbable in the foreseeable future.
5) It can be seen that the present best performing marine gas turbine, the LM 2500 (TIT = 2150° F, PR = 16.8), is operating at approximately optimum PR for maximum specific power but far below that for

maximum thermal efficiency. Apparently this is the result of removing the front fan of the TF39 (LM 2500 parent engine) which reduced the overall PR from a more nearly optimum 26 to the 16.8 given above.

6) From Figure 3.1 for the probable expected component performance given in the previous section, it is estimated that the aircraft derivative simple cycle marine gas turbine (TIT = 2600° F, PR = 32) can be expected to reach a maximum thermal efficiency of about 38% at a specific power of about 240 SHP/LB/sec. At a slightly lower PR, the specific power would be increased significantly with only small decrease in efficiency.

7) Heavy duty simple cycle engines will have efficiencies and specific powers somewhat less due to a probable lower TIT coupled with a lower PR.

Regenerative cycle performance characteristics with thermal effectiveness values of 70%, 80%, and 90% are given in Figure 3.2 (23). It can be seen from the figure that the optimum PR for thermal efficiency for a given TIT is much lower than that for a simple cycle. From this it can be seen why aircraft derivative turbines with their high pressure ratios are not

likely to be fitted with regenerators. As far as the likely performance of a regenerative cycle gas turbine in the future, if a TIT of about 2400° F is assumed, then a maximum efficiency of about 41% (at a PR of about 10) can be expected for a reasonable size regenerator with an effectiveness of 80%. The specific power for this condition would be about 240 SHP/LB/sec. Note the specific power can be increased only slightly by changing the pressure ratio (in this case increasing it as opposed to decreasing it in the simple cycle case). Because of the increased pressure losses in the regenerator, the work per pound of air and therefore specific power will be slightly less for a regenerative cycle than for a simple cycle even though the efficiency is increased for the same cycle conditions.

The other cycle configuration to be discussed is the combined cycle in the form of a gas turbine exhausting into an unfired boiler where the vapor is generated for a vapor engine operating on the Rankine cycle. Figure 3.3 (23) gives the estimated performance for a simple cycle gas turbine combined with a steam cycle, while Figure 3.4 (55) is for a simple cycle gas turbine combined with a Refrigerant 21 cycle. Note that the steam cycle in Figure 3.3 is a high pressure reheat plant with a high efficiency, 38.8%. The R-21 cycle has a lower efficiency. Figure 3.3 indicates the possibility of about 50% thermal efficiency for a TIT of 2600° F in the gas turbine and specific powers on the order of 375 HP/LB/sec. Marine steam turbine installations would most likely not be of this high

efficiency, high pressure reheat design and therefore the efficiencies and specific powers would be somewhat lower. Results shown in Figure 3.4 which are for lower TIT's than are to be expected in the future indicate that a gain in maximum efficiency of about 10% over a regenerative cycle and about 30% over a simple cycle are possible. Also that gains in maximum specific power of up to about 30% over both the simple and regenerative cycles can be obtained. (55). It appears dangerous to attempt to extrapolate these percentages to higher TIT's and different cycle conditions, but they give an indication of the improvement in both efficiency and specific powers of gas turbine engines using combined cycles. If these percentage improvements were achieved over the expected future performance of the simple cycle plant, it would result in a thermal efficiency of approximately 49% and a specific power of about 310 hp/lb/sec. Another interesting aspect of the study by Bindon and Carmichael (55) is the very substantial reduction in vapor turbine size for same power output possible using a working fluid such as Refrigerant 21 instead of steam. The R21 turbine would have much smaller diameter plus fewer stages than the steam turbine.

There are many other cycle perturbations that could be considered such as the use of compressor intercoolers or turbine reheaters in combination with each of the above cycles but to keep space and weight requirements down and to achieve the reliability necessary for a marine propulsion plant it is

doubtful if these added complexities will be incorporated in many plants and will not be considered here.

3.1.3. Fuels

In considering what fuels are likely to be used in marine gas turbines of the future, at least three seemingly diverse but interrelated questions arise:

1) What fuels will future gas turbines be able to burn?
2) What fuels will be available (and at what price) for the future gas turbine?
3) What fuels will the gas turbine be allowed to burn by various pollution regulations?

Much development effort is currently being directed toward the utilization of heavy distillate fuels in aircraft derivative marine gas turbines. Part of this effort is a result of the U.S. Navy's decision to go to a multipurpose distillate fuel for use in boilers, diesel engines and gas turbines. (40). As a result of this effort, the present aircraft derivative turbine will probably be able to operate on heavy distillates with acceptable reliability and maintenance costs in the very near future. However, it is also most probable that because of all the special requirements placed on aircraft fuels, as mentioned in Section 2.3.4., that new aircraft engines developed will continue to utilize the light distillate fuels in aircraft service. This means that conversion of these engines

to heavy distillate use will remain part of the marinization process and will continue to require extensive effort in combustor design and development of suitable turbine blade materials and/or coatings as the turbine inlet temperatures of these engines continue to rise. It does appear highly unlikely that either present aircraft derivative engines or future ones will ever be adapted to utilize residual fuels. Even if the corrosive ash deposition problems were to be overcome somehow, the much higher emissivity of the residual-oil flame would require very extensive changes in the aircraft engine combustion system.

The current interest of heavy duty gas turbine manufacturers in the development of residual-oil burning gas turbines appears to be at a rather low ebb. (Section 2.3.4.). The present method of pre-treatment of the residual fuel by water washing together with the addition of corrosion inhibiting additives while apparently the only feasible method (and some feel that it is not feasible (46)), has several drawbacks as was explained previously. However, present research work is being conducted toward reducing the need for a major portion of the pre-treatment, and toward corrosion and deposition reduction. (46, 57). The exact nature of this work or what degree of success has been achieved is not available at this time. It appears likely that for the next several years at least, the rather extensive pre-treatment will continue to be required to utilize residual fuels in marine gas turbines.

The question of what fuels will be available in the future and at what prices appears to be a very complex one and gives rise to several divergent views. (46). By the development work that some gas turbine manufacturers and the U.S. Maritime Administration (MARAD) (46, 57), are doing on residual burning gas turbines and by the continued development of residual-oil burning marine diesel engines, it appears likely that residual-oil fuels will continue to be available at least for the next several years. As for the relative prices of distillate and residual fuels, there is evidence to indicate that as fuel prices have continued to rise in recent years, the differential between diesel fuels and residual-oil fuels has remained approximately constant, resulting in the ratio of diesel fuel cost to residual-oil fuel cost decreasing. (12, 46, 58). The heavy distillate cost is intermediate between the diesel and residual. The present diesel fuel cost to residual fuel cost ratio has decreased to approximately 1.5:1, with indications that this ratio will further decrease. (12, 58). A continuation of the decrease in this ratio may reduce the effort to develop residual fuel burning engines.

As for the pollution question, this is so loaded with political and emotional considerations that it will not be considered at length here. It should be noted that land-based power plants in many countries operate under increasingly strict pollution controls but what effect these kinds of controls will have on utilizing heavy fuels in marine power plants is still largely unknown.

3.1.4. Maintenance and Reliability

Any attempt to assign mean time between failure (MTBF) values (as used in usual reliability analysis) for gas turbines in marine propulsion application appears to be questionable because the number of operating hours of these engines in this usage is not great enough at this time to be of statistical significance. Instead, one can consider specific applications where data is available, the manufacturer's predicted reliability and maintenance requirements and the performance in other applications.

The aircraft derivative gas turbines and the heavy duty gas turbines should be considered separately since the reliability and maintenance philosophies for these engines appear to differ considerably as has been pointed out earlier. The aircraft derivative gas turbine is light and compact and in general is designed for a comparatively shorter life for the critical 'hot section' components of the engine. For marine installations this type engine therefore usually is designed for rapid complete replacement of these parts by replacing the entire gas generator section which is then overhauled in a shore-based installation. On the other hand, the heavy duty gas turbines are normally specifically designed for long lifetimes, resulting in larger, heavier engines which are designed to be repaired in place.

One specific application of an aircraft derivative gas turbine for which reliability and maintenance data in the form

of time between overhauls (TBO), which as stated above for this type turbine implies gas generator changeout, is frequently quoted (46) is in the GTS Adm. William M. Callaghan. (This installation has been mentioned several times earlier and is more fully described in Appendix A.) Of the first two engines, FT4A-2's, installed in Callaghan, one gas generator was removed after 3,375 hours of operation for planned inspection because of the new application. As a result of this inspection, the other gas generator was not removed until after 5,018 hours of operation. The second gas generator changeout was not planned and was the result of a fuel manifold leak which caused damage to the combustor section. (10). Both of these changeouts were accomplished rapidly (neither exceeded 40 hours) and further design changes were made to the installation to further facilitate gas generator changeout. Other changeouts have occurred since then but some were due to attempts to utilize heavy distillate fuels and also one FT4A-2 was completely replaced by a LM 2500. (46). The operators of the Callaghan (10) feel that a TBO of 8,000 hours is not unreasonable in the near future. This is with operation on marine diesel duel with the gas turbine operating at normal rating as given in Table 2.2.

Considering heavy duty gas turbine installations, a GE heavy duty engine in the GTS John Sergeant operated for 9,270 hours on residual fuel. Examination of the critical hot parts of the gas turbine unit after this 9,270 hours of operation showed no repairs or replacements required. (2). It should

be noted, however, that this was several years ago and the engine had a TIT of only 1450° F, considerably below that of present heavy duty gas turbine design.

Gas turbines installed in fast patrol craft have exhibited shorter TBO's because of the more severe operating conditions. As an example of this, the expected TBO for the Proteus engines in the British Navy Brave-class patrol boats has only recently been extended to 2,000 hours. (32).

As perhaps typical of predictions of an aircraft derivative type gas turbine manufacturer Pratt & Whitney predicts, for the FT4 type engine, TBO's of 12,000 hours by about 1972 and increasing to 16,000 hours by 1980. (59). For any newly developed engines it is expected that the TBO will start at a low level and progress upward as has usually been the case in aircraft service. (59, 60). The above predictions are for a diesel fuel or lighter distillate and it is not known how much they would change for a heavier distillate fuel.

In addition to the gas generator changeouts discussed above, other more minor maintenance work is usually required for the aircraft derivative engine consisting primarily of inspections and water washings. The most significant inspection is the hot section inspection which, for the FT4, Pratt & Whitney estimates requires three men and a total of 12.5 man hours. It is to be accomplished about every 2,000 hours presently. This is expected to increase to every 4,000 hours by 1980. (59).

For the heavy duty gas turbine General Electric estimates that overhauls will be required about every 24,000 hours for marine applications in the 20,000 to 30,000 shp range operating on treated residual fuels. (17). This overhaul is to be conducted in place and consists primarily of replacing combustion liners and transition pieces, replacing first and second stage turbine nozzles, inspection and repair of first stage turbine buckets and inspection of compressor blading and bearings. It is estimated to require about 450 man hours. In addition to overhauls, there are also other normal maintenance actions required, the most significant of which is the replacement of combustion liners and transition pieces and of first stage turbine nozzles at 12,000 hours. This action requires an estimated 90 man hours. After service experience is gained with a specific installation, the overhaul period can be adjusted consistent with demands of the installation to a high of about 30,000 hours and after the first year the intermediate action described above can be eliminated. (17). No significant change in these estimates is expected in the next few years.

The manufacturers estimates are based primarily on experience in land-based industrial applications such as electrical power generation, pipeline pumping and etc. with limited marine propulsion experience factored in. This is true for both aircraft derivative and heavy duty gas turbines.

3.1.5. Development Support

It appears rather clear that marine applications are not able to support developments of propulsion engines on the same scale as aircraft applications $50 to $200 million per program. (46). Therefore, the lead in gas turbine engine development will continue to rest with the aircraft industry and much marine development effort will be directed toward marinizing these engines including provisions for the burning of heavier fuels. The heavy duty gas turbine manufacturers will apply the advances of aircraft engine technology where deemed applicable such as in materials development, but most of the development support for the heavy duty gas turbine industry will continue to come from land-based applications such as power generation, compressor prime movers, gas line pumping units, and etc. These heavy duty gas turbines will also require development support, although probably a lesser degree than the aircraft engines, to make them suitable for marine use.

Most of the marine gas turbine development support in the past has come from governmental agencies, either various navies or maritime agencies. This support has come primarily from the United States and England. (Russian gas turbines are not included in this discussion since so little is known of them.) This governmental support is likely to be about the only marinization support in the future too since the number of commercial marine applications is still extremely small.

One result of this is that although one can find several

aircraft gas turbines that would appear to be excellent candidates for marinization their actual conversion for marine use will continue to be slow. In other words, the potential market just does not exist that would justify the manufacturers taking the risk of marinizing these engines on their own. This type of problem is not as great with heavy duty turbines since the marinization is not as great. However, special marine development efforts such as a reversing turbine, shipboard residual fuel treatment methods, etc. will have to continue to be supported by an agency such as MARAD at least for the next several years.

In view of the above, it appears reasonable to examine briefly what type of marinization efforts the above agencies are likely to support in the future.

The British navy appears to be rather firmly committed to aircraft derivative type gas turbines for propulsion purposes (31, 32) so their development support will likely be in this direction, and because it is governmental support it will most likely go to a British firm, Rolls-Royce.

The U.S. Maritime Administration (MARAD) will probably continue support of heavy duty gas turbine development for marine purposes as it has in the past (57) although this may change as the result of a marine propulsion study currently being conducted for them.

The U.S. Navy's development efforts appear to be directed toward development of a number of aircraft derivative gas turbine modules comparable in performance and specific weight and

volume to the LM 2500. (21, 46). This would allow the needs of small, intermediate and large ships to be met by a common family of gas turbine engines whose lower power range would allow them to double as ships service generator drives as well as propulsion units. (21). Currently, it appears that the development of one of these modules in the 4,000 hp range is underway. (46).

The relatively few sources of support available for marine gas turbine development indicates that the actual number of different models of gas turbines available for marine propulsion will continue to be small in the foreseeable future.

3.2. Reversing Capability

As was discussed in Section 2.3.2., the method of providing for thrust reversal in a marine propulsion application utilizing the uni-directional gas turbine is a serious consideration. The means most often utilized for providing the thrust reversal in the past has been by the use of controllable, reversible pitch propellers as previously discussed. It appears likely that this will continue to be the primary method in the future although there are certain problems connected with the use of CRPP's, particularly for larger horsepower applications.

For hydrodynamic considerations it becomes necessary to increase the propeller blade area as power requirements are increased. CRPP's are limited in the size of blades that can be used by the clearance required to allow the blades to pass

each other satisfactorily in reversing pitch. It is estimated that the maximum expanded area ratio allowable for a 5-bladed CRPP is about 0.8 for no blade interference when reversing pitch. It is slightly less for a greater number of blades and more for less blades. This together with diameter and rpm considerations appear to limit the horsepower per CRPP for ships of the destroyer, destroyer escort size range to the region of 40,000 to 50,000 SHP. (27). For larger ships with correspondingly larger allowable propeller diameters, the horsepower limit is greater. For instance, Lips N.V., who are furnishing the CRPP's for the 30,000 hp per shaft Canadian DDH and for the 30,000 to 35,000 hp per shaft gas turbine powered Sea Train container ships, feel that 60,000 hp CRPP's for container ships are feasible in the near future. (11).

In addition to the hydrodynamic problems associated with higher powers in CRPP's, the hydraulic-mechanical pitch changing mechanism in the hub of these propellers is faced with higher torque requirements both in maintaining and changing blade pitch under load. These higher torque requirements together with the requirement to keep the diameter and length of the hub small both for hydrodynamic and weight reasons leads to higher design stresses in the metals and to higher hydraulic pressures with their associated sealing problems. These problems together with the hydrodynamically influenced push for smaller blade clearances at zero pitch make the reliability of these higher power level CRPP's questionable, and they are yet to be proven

in service.

The 30,000 hp Lips CRPP's will soon be in service on the DDH 280 and the Sea Train Euroliner and the U.S. Navy appears committed to 40,000 hp CRPP's on the DD963 class so that service experience on these higher power level CRPP's will become available in the next few years. In summary then, indications are that CRPP's with acceptable reliability will be available in the near future for destroyer/frigate type ships in power levels up to 40,000 - 50,000 shp range and for larger ships in power levels up to and somewhat greater than 60,000 shp.

Considering other methods of thrust reversal, the use of reversing reduction gears appears to be the next most likely method to be employed in the future. The installation in the Callaghan of reversing reduction gears with friction clutches has apparently given satisfactory reliable service with some minor design modifications. (10, 61). The friction clutches used inherently experience wear in service, particularly in the Callaghan application where low speed maneuvering is accomplished by slipping the clutches. However, the expected life of the clutches is rather long, approximately six to eight years estimated for Callaghan. (10). The energy dissipation required for reversing reduction gears could also be handled by fluid couplings. These would be a relatively higher cost component than friction clutches requiring pumps, coolers, piping, etc., but would not be expected to be replaced during the ship's lifetime. (17).

As mentioned before, electrical transmission is presently feasible but not often used because of its relatively high weight, size, high cost and low efficiency. The use of superconductors in the electrical machines would greatly reduce the size and weight problems but this development will probably not appear for several years.

Another method possible is to use a hydrodynamic reversal torque converter. (30). During ahead motion, a hydraulic coupling transmits power of the gas turbine to a gear box while the direction of rotation is reversed in the reversing converter. The transmission system is controlled by filling and emptying of the hydraulic circuits, the coupling being filled for ahead motion with the converter being empty and vice versa for astern motion.

The last method is to modify the gas turbine itself to provide reversing. In August, 1970, MARAD entered into an 8 million dollar, 5-year cost sharing contract with General Electric for the refinement of industrial gas turbines for shipboard use. (57). One of the specific development areas is in reversing techniques, among which is to be the continued development of a reversing axial flow gas turbine.

3.3. Ship Applications

Naval warship and merchant ship applications of gas turbine propulsion will be considered separately because the differences in operating profiles and design and effectiveness considera-

tions are normally quite different. Naval support or auxilliary ships such as oilers and other types of fleet replenishment vessels are similar to merchant ships in operating profile and many design considerations. It is generally agreed that unconventional craft such as hydrofoils or hover craft will continue to require the light weight, high power propulsion plants which can only be satisfied by utilization of aircraft derivative gas turbines so no further consideration of these vessels will be made.

3.3.1. Naval Warships

The usual operating profile as previously described for naval warships is normal cruising at low speeds for long periods of time with periodic high speeds of relatively short duration required. This profile led to the combined plant concept where one type of propulsion prime mover is chosen to supply the base load or cruising power and another prime mover of a different type or as in the case of a COGOG plant of the same type but with higher output is chosen to supply 'boost' power. As discussed in Section 2.1., the majority of marine gas turbine propulsion horsepower is presently utilized as boost power in combined plants. Also, most of the gas turbines utilized in this application are of the aircraft derivative type. There appears to be rather general agreement (46) that almost all future non-nuclear warships will utilize aircraft derivative gas turbines for 'boost' propulsion. The biggest question seems to be concerned with how base load power will be pro-

vided.

In discussing the gas turbine as a possible base load power source, further discussion of some of the warship design and effectiveness considerations referred to above is in order.

Practically all modern warships are volume limited ships, not weight limited. This means that in the normal preliminary design of a warship, the first step is to attempt to find space for everything. Furthermore, the volume required can not be just any volume, it is actually more descriptive to talk in terms of deck area required such as in berthing and messing spaces for crew members, all of the various plotting rooms and electronic equipment spaces, and etc. What this means is that the amount of space and more particularly the type of space required by the propulsion system including endurance fuel becomes very important. Often by utilizing an aircraft derivative gas turbine for the base load power plant it becomes possible, because of the relatively low height requirements of aircraft derivative gas turbines in particular, to put another compartment over the top of the engine room (in comparison to competing prime movers), gaining some very valuable deck area. This is one place where increased specific power is important, to assure that the gained deck area is not taken up by inlet and exhaust ducting.

Another consideration is that even if a competing plant has a better specific fuel consumption so that the total volume required by the gas turbine plus endurance fuel is greater

than for the competing plant, much of the gas turbine plant's space requirments will be for fuel storage which is rather low "worth" volume that is not much good for anything else as in the turn of the bilges, etc. An additional advantage in this case is that by the gas turbine plant requiring a larger amount of fuel for the specified endurance, the 'boost' plant will have a greater endurance.

Some additional attributes of the gas turbine which are rather important effectiveness parameters for a warship prcpulsion plant are:

1) the quick startup capability
2) the relative ease of automation
3) the possibility of high reliability because of relatively few auxilliaries
4) high ship availability for the aero derivative type utilizing gas generator change-outs.

If one factors in the additional advantages of crew training, possible spares interchangability, etc., it becomes possible to understand why the Canadian DDH and the British Type 42 DD and Type 21 frigate as well as the U.S. DD 963 are all gas turbine plants even with the relative poor thermal efficiency of first generation aircraft derivative gas turbines available. (The DD 963, even though now planning to use the LM 2500 with considerably better efficiency than the first generation engines, was not designed specifically for it.)

It appears from these considerations that as the reliability of the second generation aero derivative gas turbines are proven and as comparable lower power level engines become available for low power base load and ship service generator prime movers that almost all non-nuclear warships of the future will be built with all aero derivative gas turbine propulsion plants. Whether the plant will be COGOG or if all the gas turbines will be of the same power level will depend to a large extent upon the relative base and boost load requirements as well as on the part load efficiency of the future gas turbines. It does not appear that the ability of the heavy duty gas turbine to utilize residual fuel oil will be a factor in warship propulsion considerations because reliability gained by burning the distillate fuels appears to be more important than the savings to be realized in using the residual oil. This is evidenced by the U.S. Navy's decision to use a multi-purpose distillate fuel even in boilers.

3.3.2. Merchant Vessels

Propulsion plant considerations are quite different for merchant vessels than for naval ships. For merchant vessels the consideration becomes much more of an economic one than with a warship. This is not to imply that economic aspects are not also very important in warship propulsion plant selection, but in the warship case there are also many factors which relate to the mission effectiveness of the warship. A

desirable warship effectiveness factor, for example, is the quick starting capability of the gas turbine where as for a merchant vessel it is normally not very important. In the merchant vessel case its "mission" is normally to make a profit for the operator so the factors which relate to the "mission" effectiveness are necessarily economic ones primarily relating to operating costs or acquisition costs.

There have been a number of papers published in recent years on the use of gas turbines for merchant ship propulsion. (10, 43, 49, 53, 60, 63, 64). Of these, the study done by Hempel and Reulein (49) is one of the most recent and also one of the most comprehensive.

This study consists of economic comparisons of gas turbine, diesel and steam plants for a number of different ship types, both volume and weight limited, over a wide range of displacements and service speeds. Two of the principal results of this economic comparison are that:

1) The aircraft derivative gas turbine with an SFC of about 0.40 lb/hp/hr (comparable to LM 2500 performance) is superior to the other plants for general cargo ships and smaller container vessels with power requirements below 20,000 hp.
2) The regenerative heavy duty gas turbine (with intercooler) having an SFC of about 0.42 lb/hp/hr is competitive with the other

plants for all the types of ships considered particularly in the higher power range.

The conduct of such a broad study involving so many different ship types and propulsion plant concepts necessarily requires the making of a large number of assumptions in order to generate quantitive results. Therefore, it appears that the important results are not that the gas turbine is superior over this or that power range for some particular ship type but instead that over all of the power ranges for all the ship types considered, the two types of gas turbine plants described above are relatively close to the other plants in terms of economic performance. In other words, even for the ship types or power ranges for which both gas turbine plants appeared to involve higher freight costs, the costs were close enough so that some changes in manning level requirements, using a heavy distillate instead of marine diesel in the aircraft type engine, higher availability assumption for gas turbine plants and possible other minor assumption changes would be enough to make the gas turbine plant superior in performance. What this means then is that the gas turbine plants of the types described above are at the point today where they should not just arbitrarily be ruled out as propulsion plants, instead they should be carefully considered in almost all cases with particular design consideration being given to utilizing the special features of the gas turbine. An example of this is in the Sea Train con-

tainer ships previously mentioned.. The four 23,000 d.w.t. ships will have propulsion horsepower exceeding 60,000 shp each with service speeds in excess of 25 knots and will utilize first generation aero-derivative marine gas turbines, Pratt & Whitney FT4A-12's. From Hempel and Reulein's study it would appear for this type of ship, its size and speed, that any of the other competing propulsion plants would be better suited particularly with the FT4A-12's relatively high fuel consumption.. But apparently, detailed studies for this particular application show that by achieving a significant reduction in manning utilizing a general purpose crew, by considering the higher availability possible with the expected reliability and low shipboard maintenance requirements of the FT4 engine, and by using a lower cost heavy distillate fuel, the simple cycle aircraft derivative gas turbine plant is the best choice.. (12). This indicates that gas turbine plants are competitive enough with other plants to justify detailed studies for individual applications in most cases.

Presently, one problem in using aircraft derivative gas turbines for propulsion purposes is that the engines are not available in a continuous range of powers, particularly better performing second generation engines. This situation is expected to improve in the near future primarily due to naval development efforts. Another development expected in the very near future that will make the aircraft derivative engines more desirable for merchant ship propulsion is the demonstration of the second generation engine's reliability on a heavy distillate. (46)

The use of a combined gas turbine and vapor engine cycle is not considered in the Hempel and Reulein study other than to assume that gas turbine exhaust heat would provide steam for ships service power generation requirements which are usually low for merchant ships. As was previously discussed in Section 3.1.2., use of a combined cycle can result in improvement of thermal efficiency and specific power of up to 30% over that of a simple cycle gas turbine. It would appear that most merchant ship operating profiles of long periods at a steady power level with little maneuvering required would be well suited for the use of a combined cycle. The increase in specific power would help in keeping the plant from getting too large and if a refrigerant were used in the vapor cycle as discussed earlier, the overall size and weight of the combined cycle plant might be less than the simple cycle gas turbine plant alone of the same power level. The added control complexities of the vapor cycle with the consequent lowered reliability will probably keep the combined cycle from being acceptable in the near future for warship propulsion but appear to be suited to many merchant ship applications.

Gas turbine plants are presently competitive for most merchant ship applications and further increases in efficiencies and specific powers are expected. Also, aero-derivative engines are expected to be able to utilize cheaper, heavier fuels in the future. Considering this, it would appear that one could expect a significant growth in commercial marine gas turbine propulsion

applications in the next decade. However, this would be overlooking the traditionally conservative nature of the shipping industry. The inability to point to any non-government owned merchant vessels with gas turbine propulsion currently in service is a serious deterrent to this expected growth. Perhaps, once the Sea Train container ships and the BHP roll on/roll off ships are in service, and with increased naval applications allowing ship owners to gain more confidence in the gas turbine as a marine propulsion plant, the significant increase in commercial marine gas turbine horsepower long predicted will become a reality.

4. CONCLUSIONS

The main conclusions of this study of marine gas turbine propulsion plants are as follows:

1) Most non-nuclear warships built in the future are expected to be entirely propelled by aero-derivative gas turbines. Both COGOG plants and propulsion plants utilizing only one size gas turbine will be used.

2) A significant increase in the use of gas turbines for merchant ship propulsion utilizing both aero-derivative simple cycle and the heavy duty regenerative gas turbines is expected. The aero-derivative engines will utilize a heavy distillate fuel while the heavy duty engine is expected to operate primarily on treated residual fuels at least for the next few years. One deterrent that must be overcome is the traditional reluctance of shipowners to accept a new type propulsion plant.

3) Satisfactory thrust reversal with gas turbine propulsion can be achieved by using a controllable, reversible pitch propeller presently at power levels up to about 30,000 hp per shaft. In the next few years this power range is

expected to be extended to about 40,000 to 50,000 hp per shaft for destroyer type ships and to over 60,000 hp per shaft for larger vessels. Other means of thrust reversal are also available with a reversing gear appearing the next most promising method.

4) Simple cycle aero-derivative marine gas turbines are expected to achieve a thermal efficiency of about 38% in the next decade by the use of higher turbine inlet temperatures and higher compressor pressure ratios. The specific power of these engines will be greatly increased. No major breakthrough in high temperature material development is anticipated so these high turbine inlet temperatures will require advanced blade cooling techniques to be employed.

5) Heavy duty regenerative marine gas turbines can be expected to reach a thermal efficiency of about 41% in the next decade with approximately the same specific power as the aero-derivative simple cycle engines. It is very doubtful if these gas turbines will be able to use residual fuels at the high turbine inlet temperature required to achieve this

high efficiency.

6) Within this same time frame, the combined gas turbine and vapor cycle engine is expected to have the potential of attaining a thermal efficiency of 48 to 49% with much higher specific powers than either the simple cycle or regenerative type gas turbines alone. This type of plant appears to be well suited to many merchant ship applications.

7) The availability of high performance aero-derivative gas turbines over the entire power ranges desired for marine propulsion plants will continue to be a problem in the future primarily because of limited support available for marinizing suitable aircraft engines.

8) The improvement of the heavy duty gas turbine's ability to use residual fuels does not appear to interest very many gas turbine manufacturers at this time. There is some question as to whether the ability to utilize residual oils is worthwhile because of a continuing decrease in the price ratio of diesel fuel to residual oil and also the possibility of future pollution regulations preventing the use of the residual oil fuels.

9) Hot section corrosion aggravated by the ocean

environment will continue to be a problem for marine gas turbines. This problem will require more effort as turbine inlet temperatures continue to rise. Also the use of heavy distillates in aircraft derivative engines will compound the problem for them.

10) Air inlet and exhaust ducting arrangement will continue to require special design attention and close coordination between the naval architect and the marine engineer. The expected higher specific powers of future gas turbines will lessen this problem somewhat.

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A.1. GE INTEGRATED GAS TURBINE POWER PLANT (17, 43)

SHIP

MARAD cargo vessel design PD108	
Length between perpendiculars	528 ft.
Beam	81 ft.
Deadweight	10,000 tons
Design study (no ship built)	1964

MAIN PROPULSION SYSTEM

The propulsion system consists of a 20,000 hp regenerative gas turbine driving a controllable-reversible pitch propeller through reduction gears. The gas turbine exhaust heat is utilized in a heat-recovery boiler to provide steam to drive a turbo-generator, for the ship's distilling plants and for the ship's heating for fuel and hotel services. The gas turbine uses residual fuel oil which is treated in an on board treatment system consisting of washing, additive and an analytical systems.

The engine room arrangement is shown in Figure A.1. The following table gives some of the major machinery weights:

Gas Turbine	65.7 Tons
Regenerators	112.4
Reduction Gear	67.0
Waste Heat Boiler (including forced draft blower and fuel system)	39.7

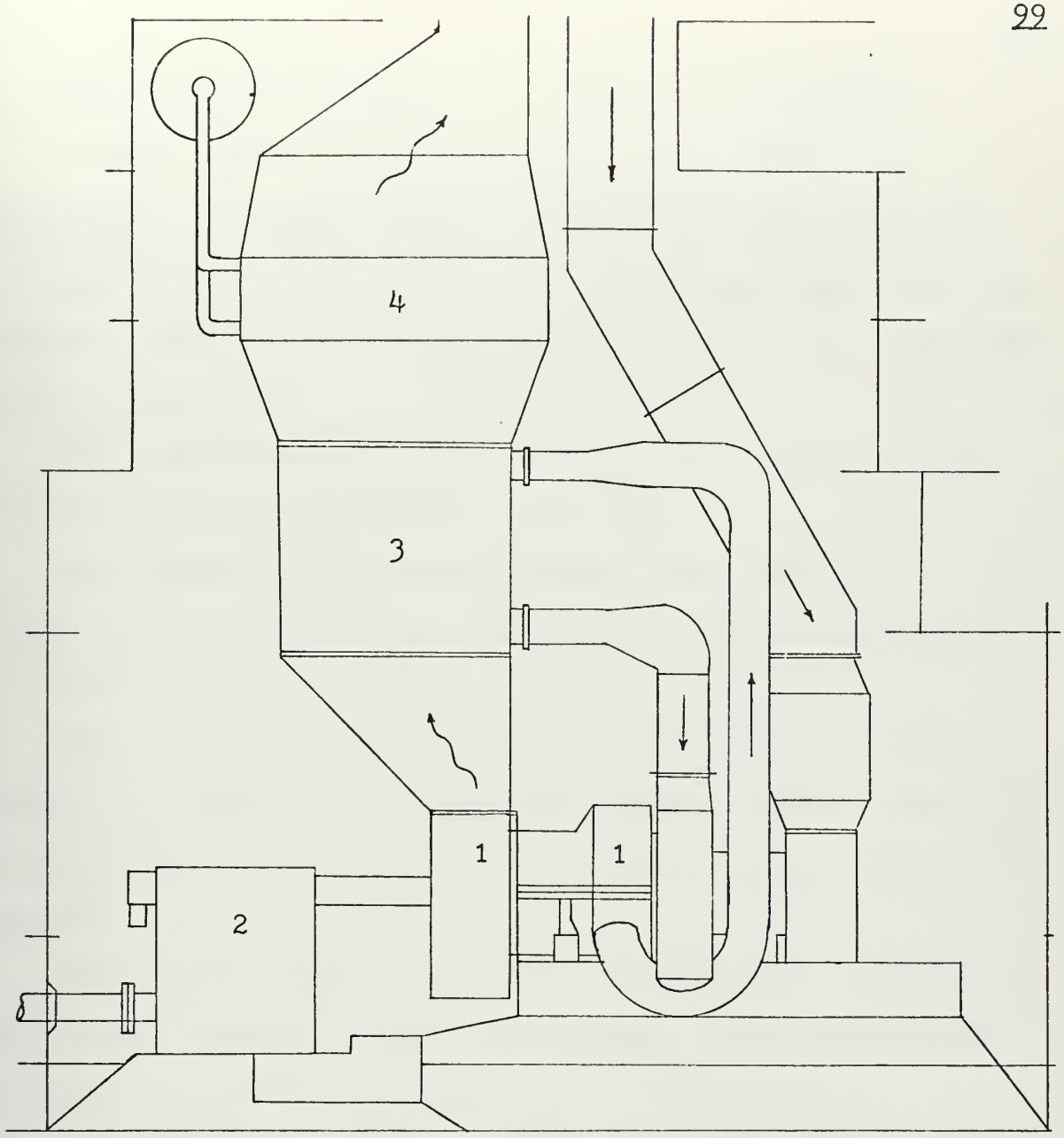

FIG. A.1 Engine Room Arrangement for Integrated Gas Turbine Power Plant Design.(43)

1. Main Turbine
2. Main Reduction Gear
3. Regenerator
4. Heat Recovery Boiler

Fuel Treatment System	5.5 Tons
Uptakes, Ducts and Stack	30

Gas Turbine The gas turbine is a regenerative, open cycle two shaft turbine. The compressor is 16 stage axial flow with pressure ratio of 6.36:1 with air flow of 254 lbs/sec and operating at 3,860 rpm.

The combustors are 8 Louvered type, fuel based on specification Bunker C and atomized by steam.

The high-pressure turbine, driving the compressor, is a single stage axial flow type with turbine inlet temperature of 1477° F.

The low-pressure load turbine is also a single stage axial flow type with gas exit temperature of 888° F operating at 3,600 rpm. It is equipped with variable angle nozzles for control.

The starting device is a 635 hp steam turbine which utilizes steam generated in the heat recovery boiler with auxiliary gas generators supplying the hot gas required.

The regenerator is a plate-fin, sectional type with 77% effectiveness.

Reduction Gears The reduction gears are double-reduction, double helical, articulated locked-train type rated at 20,000 hp and having speed reduction of 3600/570/105 rpm. The "K" factor of the low speed pinion is 105 and of the high speed pinion is 160. The reduction gear lubrication system is

integral with the turbine's lubrication system.

Propeller The propeller is a 4-blade controllable and reversible pitch type, 21 feet in diameter, and rated to absorb 20,000 shp at 105 rpm.

Air and Exhaust Ducting The air inlet for the gas turbine is located topside on the navigating bridge deck, about 53 feet above the water line. A plenum chamber about 25 feet long by 25 feet in breadth surrounds the upper stack. Air is taken from the port, starboard and aft sides of the inlet house through baffles arranged vertically. The baffles consist of structural steel angles which remove large droplets of water as the air changes direction through them.

Downstream of the baffles, the air passes through woven mesh filters (Demister). The filter is supposed to remove all the remaining salt particles contained in the air either as dry particles or within vapor.

The inlet duct dimensions are about 5 feet by 12 feet 6 inches.

The exhaust ducting is reasonably straight run up from the waste heat boiler of dimensions 5 feet by 12 feet, terminating in a 8 feet 9 inches diameter smoke pipe.

Fuel Treatment Facility The fuel treatment system is provided to make the residual fuel suitable for use in a high

temperature gas turbine. This system consists of three sections, as follows:

1) Desalting or Washing Section

The removal of sodium, potassium and calcium from the raw residual oil to acceptable limits is accomplished by means of a combination oil washing and centrifuging procedure.

2) Additive Section

A blending of a suitable additive (presently magnesium sulfate) with the fuel prevents corrosion action by inhibiting the vanadium. The vanadium compounds are mostly oil soluble, therefore were not removed in the desalting section.

3) Analysis Section

The fuel analysis section is used to monitor the quality of both the delivered and treated fuel oils. To check the performance of the washing system, an occasional check of the sodium in the washed fuel is required and each time a new batch of fuel is introduced into the system, the vanadium content must be determined so that the amount of the oil can be determined.

The fuel treatment system is completely automated with the exception of mixing the magnesium sulfate solution once a day with the operation requiring only a short time.

A.2. SWEDISH T-121 TORPEDO BOAT

BOAT

Displacement	200 tons
Length	140 ft.
Beam	23 ft.
Speed	40 kts.
Designed	1965

PROPULSION SYSTEM

The T-121 is driven by three shafts. Each set consists of a Rolls-Royce Proteus gas turbine with 3,450 bhp continuous rating, an Allen-Stockicht primary reduction gear from 11,600 rpm to 5,239 rpm, a connecting shaft with two flexible couplings, one Allen secondary reduction V-drive including thrust block and one KaMeWa controllable pitch super cavitating propeller rotating at 1,439 rpm. The machinery general arrangement in the boat is shown in Figure A.2.

The following table gives some of the major machinery weights:

3 Proteus gas turbines	9,800 lbs.
3 Allen gear boxes plus shaft to turbine	10,500
3 KaMeWa CPP's plus shafting	8,125
Fuel, lube oil and cooling water system	5,850
Air intake, exhaust pipes with covers, cooling fans for turbines	4,600

1. Marine Proteus main turbine
2. Plenum chamber
3. Allen secondary reduction gearbox
4. Machinery control room

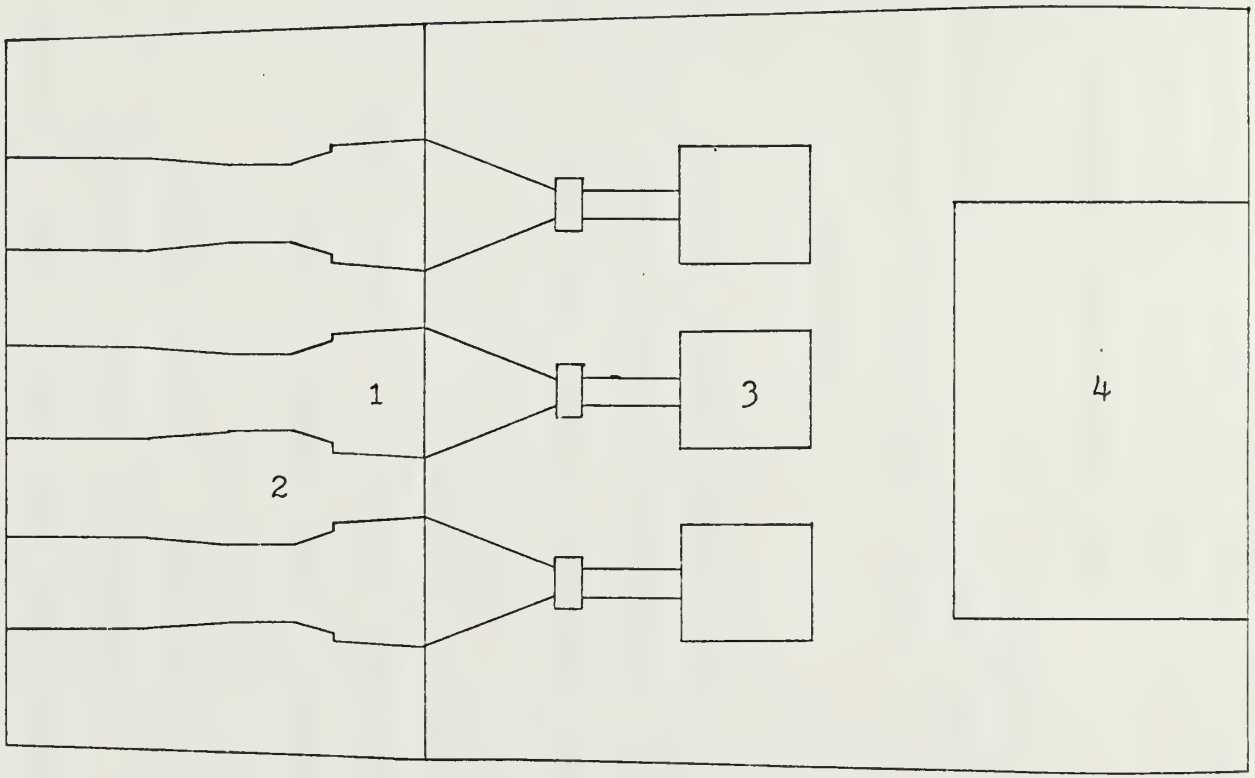

FIG. A.2 General Machinery Arrangement in Swedish T-121 Torpedo Boat.(65)

Propulsion Turbines The Proteus gas turbine used is a two shaft aircraft derivative gas turbine consisting of a gas generator and a free power turbine. The gas generator has a 13 stage compressor giving about a 7.3 compression ratio. The compressor is driven by a 2 stage axial turbine. The free power turbine which receives the hot pressurized gas from the gas generator is also a 2 stage axial type.

The gas turbine fuel system contains automatic protection against low pressure in lubrication system and turbine or compressor overspeed. The turbines utilize marine diesel fuel. Each turbine has an air start motor.

Reduction Gears The shaft which connects the turbine first reduction gear with the separate second reduction gear has rubber couplings at both ends to allow the turbine the unavoidable thermal movements as well as misalignment due to distortion of the boat and vibration. The secondary reduction gear consists of a 15 degree V-drive spiral bevel gear with a speed reduction of about 1.3:1 and a parallel-shaft, single-helix gear of about 2.8:1. Two of the three propellers rotate clockwise, the other two counterclockwise. This is accomplished by an idler train incorporated in the counterclockwise secondary gears. The secondary reduction gear is a light weight design with aluminum alloy gear case and nitrided parallel train. The bevel gear is of case-hardened steel. The shafts are carried in ball and roller bearings, except for the bull gear where

plain bearings are used. The propeller thrust bearing is located at the front end of the gear case.

Lubrication System Each gas turbine (including the primary reduction gear) has its own lube oil system with shaft driven pumps. The turbine oil is cooled in sea water coolers. Each secondary reduction gear has a separate lubricating system with two sets of pumps, one shaft driven, the other motor driven. The secondary gear oil cooler is combined with the turbine cooler both using the same flow of sea water.

Air Inlet and Exhaust System The gas turbines are installed in the intake plenum chamber as was shown in Figure A.2. The combustion air intake cowling has its aft-faced opening on top of the inclined intake trunk. One row of vertical splitters is installed both to separate water from the combustion air and to attenuate noise. The exhaust pipes are as short as possible and have a slight S-shape. They end just below deck level at the stern in a 3^{o} downward direction.

Propellers Each propeller is a super cavitating KaMeWa controllable pitch propeller with an L-type hub. Each one has 3 blades, 43 3/4 inch diameter, blade area ratio of 0.60 and designed pitch ratio of 1.17. The L-type hub is a special design by KMW with a total blade turning angle of 115 degrees which allows any pitch to be set between fully feathered ahead pitch

and full astern pitch. The requirement for the fully feathered ahead pitch was necessitated by the machinery arrangement with no clutches in the propulsion drive train.

Control System Each shaft is controlled by a single lever which controls the combined action of the propeller pitch mechansim and the turbine throttle. During normal running all maneuvers are controlled from the bridge. Starting and stopping of turbines, as well as control of feathering, are done in the machinery control room (MCR). After a start of another turbine, when the vessel is underway, it can be run up from the MCR to suitable speed. Then the bridge assumes the control and the control lever in the MCR is declutched. The function of all machinery is thereafter superintended from the MCR, with full and immediate control from the bridge.

A.3. PEDER SKRAM-CODOG FRIGATE (66, 67)

SHIP CHARACTERISTICS

Displacement	2,000 tons
Length overall	364 ft.
Beam	39 ft.
Speed	30 + kts.
Delivered	March, 1966

MAIN PROPULSION SYSTEM

The CODOG propulsion system consists of two 22,000 hp or two 2,400 hp diesel engines driving two controllable pitch propellers through reduction gears with clutches.

The propulsion machinery area is divided into five water tight compartments as shown in Figure A.3. The spaces contain, from fore to aft, portside gas turbine, portside gear and clutches, the two propulsion diesels, the starboard side gear and clutches and the starboard gas turbine. The main control room is located above the starboard gear box.

The gas turbine air inlet and exhaust ducts run close together through the decks. The air inlet is constructed as an annular horizontal grid around the base of the stack.

Normal operation is as follows. For low-speed maneuvers, the diesels are used with ship speed and direction controlled by the CP Propeller. When cruising, the diesels run close to their maximum speed and the propeller pitch is set to give

1. Gas Generator
2. Power Turbine
3. Gas Turbine Reduction Gear
4. Diesel Reduction Gear
5. Hydrodynamic Coupling
6. Diesel Engine

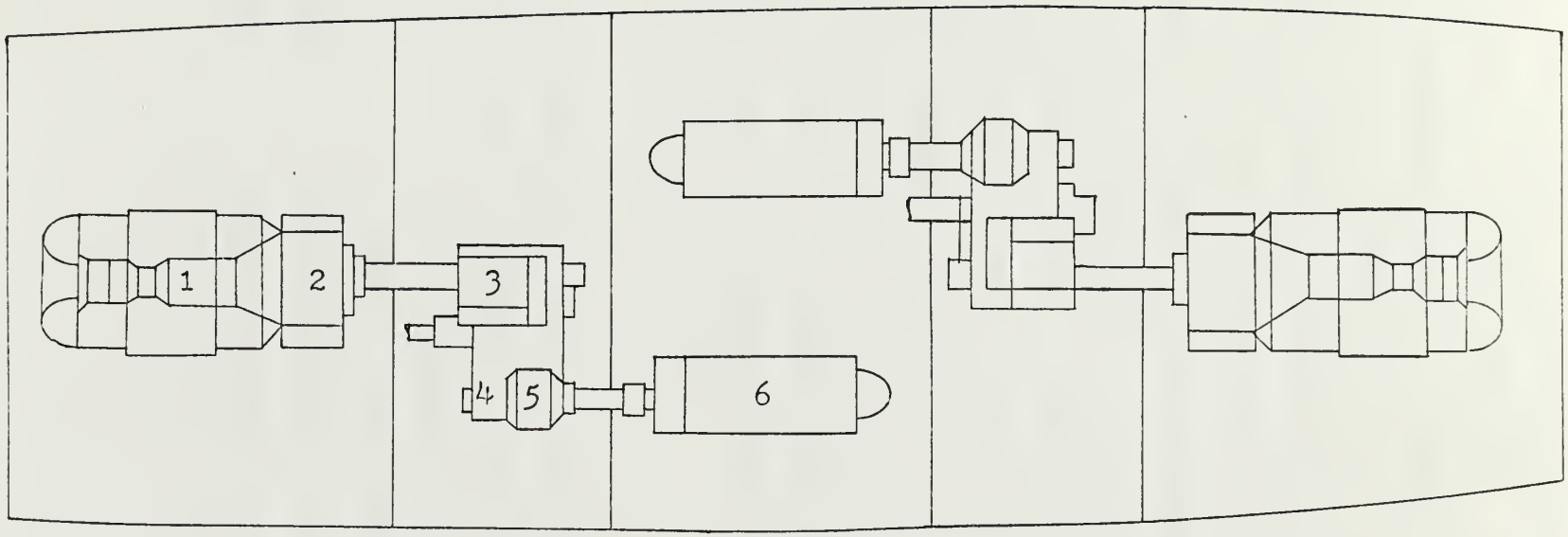

FIG. A.3 Propulsion Machinery in Danish CODOG Frigate - Peder Skram.(59,66)

optimum efficiency. When the need for higher ship speed arises, the gas turbine can be started in a very short time. The power turbine idling rpm is set slightly over that of the gas turbine gear input shaft which is already turning, to avoid running the clutch at a small relative velocity difference and thus insuring positive engagement. When gas turbine power is increased, the diesels are automatically declutched and may be run at idling speed or shut down. On changeover to diesels again, the power turbine rotor may be rotated slowly by means of frictional forces in the freewheeling clutch. The oil system and bearings are designed to permit such operation for an indefinite time. Thus, all engine speed and power regulation is done by pushing fuel control levers, as if there were a single prime mover. The diesels and gas turbines both use marine diesel fuel. Some weight and performance data is given below.

The Diesels The turbo-charged V-16 diesel engines are of General Motors type 16-567D and will drive the ship up to about 16 knots. The intermediate shaft between hydraulic coupling and gear carried tooth couplings in both ends to allow for misalignment under shock conditions and to compensate for axial displacement. The engine is mounted on shock-absorbing rubber elements to obtain the necessary shock resistance.

The Gas Turbines The major components of each gas turbine are the Pratt & Whitney Aircraft GG4A-3 (J75) gas generator and the Stal-Laval two stage reaction free power turbine.

Gas Generator The GG4A-3 gas generator is the gas generator portion of the FT4 gas turbine.

It is a twin-spool gas generator with an eight stage, low-pressure compressor followed by a seven stage, high-pressure compressor. This gives a total compression ratio of approximately 12:1. The can-annular burner has eight burner cans interconnected by crossover tubes. Fuel is supplied to the burners by eight circular clusters of six nozzles each. The first stage turbine drives the HP and the second and third stage turbines, the LP compressor through concentric shafts.

The fuel pumps, the hydromechanical fuel control unit, oil pressure and scavenging pumps are driven through the accessory gearbox. The engine is started by an air turbine powered by compressed air from storage tanks. The special synthetic lube oil is cooled by lubricating oil from the turbine gear. A compressor cleaning system is provided, utilizing distilled water injected through nozzles in the air intake. Should heavier depositions occur, a solid cleaning agent can be introduced into the compressor through the same cleaning system.

Power Turbine The power turbine consists of an inlet diffuser and connection to the gas generator, the stator and rotor,

an exhaust diffuser, and an exhaust casing which connects to the stack. The two stage power turbine has an overhung rotor mounted in two journal bearings.

The gas generator exhaust connects to the power turbine via a conical inlet diffuser. The connecting element is a radially movable, axially sliding joint which forms the gas seal. This joint transmits virtually no forces from turbine to the gas generator.

The journal bearings are of the tilted-pad type which use small radial clearances and give stable operation despite high speeds and relatively low loading. The bearing at the coupling end is combined with a Michell-type thrust bearing. An intermediate shaft with gear tooth couplings in both ends connects the power turbine and the gear. The lube oil system is common to the power turbine and the reduction gear.

Reduction Gear and Clutches and Propellers The diesel and the gas turbine work on the propeller shaft through a common Stal-Laval reduction gear. The diesel engine drives a double-helical, single-reduction gear. The gas turbine reduction gear is a double-reduction, single locked-train articulated type gear.

The Borg Warner free wheeling clutches are integral with the gear allowing independent operation of the prime movers as well as automatic change-over from diesel to gas turbine and vice versa. The locking action in the clutch is performed by

rows of "sprags" between an inner and outer ring. The sprags will roll into engagement when the outer ring starts to overtake the inner, thus locking the clutch. The sprags are mounted in two concentric cages which synchronize their movements. At high over-running speeds, the sprags are lifted off the inner race by the hydrodynamic forces in the oil film. Centrifugal forces in combination with spring forces oppose the hydrodynamic forces. When the relative speed between the sprags and the inner race decreases, the hydrodynamic forces decrease as well, and the sprags are brought into metallic contact with the inner race prior to engagement.

The gear is equipped with a direct-driven, screw-type lube oil pump turned by the second reduction pinion of the turbine gear. The capacity of the pump is adequate to meet the requirements of the gear, power turbine, clutches, and couplings. Electrical pumps take care of starting and low-speed operation. The gear lube oil is a heat sink for the gas generator lube oil. The gear oil is, in turn, cooled in sea water coolers. The controllable reversible pitch propellers are of KaMeWa design.

Gas Turbine Foundation The supporting structure for the gas generator and the power turbine assembly is a 10 foot diameter cylindrical container. The gas generator is axially fixed at the front support and hangs on links at the rear end. The power turbine connects via a straight, seamless cone to a heavy supporting ring at the end of the container. The cone

is integral with the turbine exhaust casing. At its rear end, the power turbine rests on a flexible vertical plate which allows for axial expansion only. The container has a large opening for the inlet air on top. The air flows around the gas generator and via a toroid-shaped passage to the gas generator intake. The whole air intake has been carefully wind tunnel-tested for optimum performance. The complete gas turbine assembly rests on 34 shock-absorbing rubber elements fastened to the ship's hull.

This type of foundation has several advantages and disadvantages. Among the advantages are the gas turbine can operate even if the engine room is partly filled with water to above the container center line level. Severe shocks of short duration which are transmitted by the rubber as longwave, reduced-amplitude accelerations are easily taken up by the "continuous" structures supporting the gas turbine components. The air intake duct occupies a minimum of space in the ship as it is carried close to the exhaust duct and no plenum chamber is necessary. The disadvantages of the container arrangement are that excessive oil and fuel leaks may cause contamination of the intake air, adjustments to the jet engine can not be made while running, and maintenance such as a hot-section inspection will take more than normal time, due to the limited space inside the container.

The compressor section of the gas generator is cooled by the intake air. The burner and turbine sections are separated

from the intake by a conical casing. A 10 kw fan on the container top draws cooling air through the enclosed area and discharges it into the stack. The air intake duct is connected to the container by a rubber bellows. For the exhaust, the bellows is made of steel. The expected pressure loss is 4" H_2O for the inlet and 6" H_2O for the exhaust duct and stack. The gas generator can be removed or installed through the air inlet.

Weight and Performance Data

Power	maximum	2 x 22,000 shp
	cruising	2 x 2,400 shp
SFC	maximum	0.55 lb/shp
	cruising	0.40 lb/shp
Shaft Speed		4,670 (gas turbine) rpm
		800 (diesel) rpm
Prime Mover Weight (including gear)		5.5 lb/shp
Machinery Total Weight		6.4 lb/shp

A.4. MILITARY SEALIFT COMMAND'S ADM. WILLIAM M. CALLAGHAN (10, 61, 68)

SHIP

Roll on/roll off cargo ship

Displacement	23,680 tons
Length overall	694 ft.
Beam	92 ft.
Speed	25.8 kts.
Delivered	December, 1967
Designed and built by	Sun Shipbuilding & Dry Dock Co.

The ship is a merchant vessel but was designed and built specifically as a gas turbine powered vessel to provide operating experience with high powered gas turbine ships for the U.S. Navy. However, since its delivery, it has been in almost continuous operation between East Coast, USA and Bremerhaven, Germany transporting a cargo primarily of private automobiles and loaded military sea vans.

MAIN PROPULSION SYSTEM

The main propulsion system of the ship consists of two 20,000 hp gas turbine engines, each driving a fixed pitch propeller through a reversing reduction gear. A sketch showing the layout of the main machinery compartment is shown in Figure A.4.

Reversing reduction gears are utilized as the means of

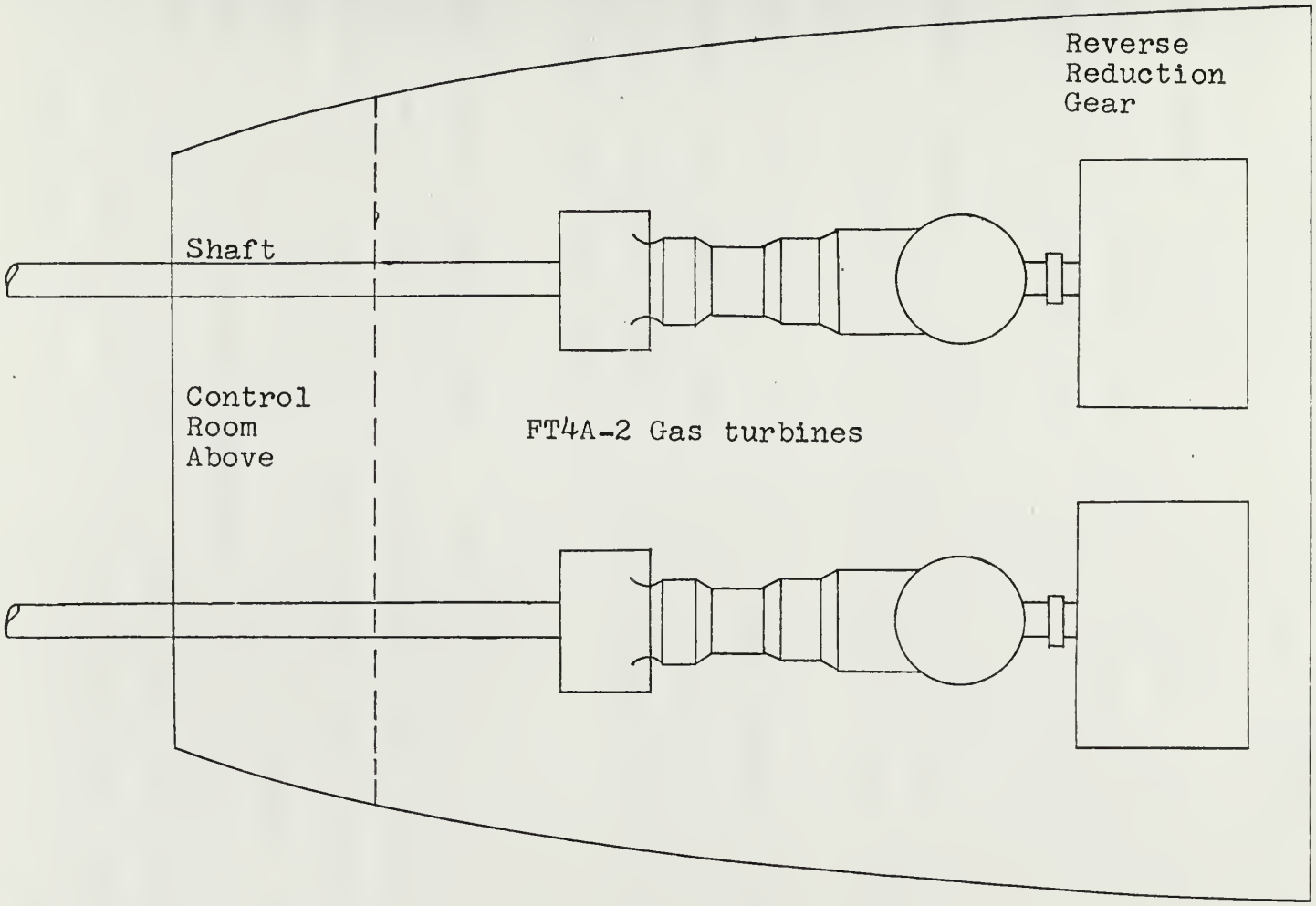

FIG. A.4 Main Machinery Compartment in GTS Adm. William M. Callaghan (59).

reversing the power output.

Engines The original engines were two Pratt & Whitney FT4A-2 gas turbines. In about 1970 one of the FT4's was replaced by a General Electric LM 2500 to gain operating experience with this new turbine.

The turbine originally used marine diesel fuel but recent attempts have been made to operate on a heavier distillate fuel similar to Navy Distillate (40) to gain experience with this fuel.

Engine starting is accomplished by using a hydraulic system with the main hydraulic start pump clutched to one of the diesel generators.

Noise in the engine room from the gas turbines is controlled by their enclosures which provide acceptable noise levels.

The gas generators can be removed through a bolted plate in the deck above the engine room.

Reduction Gearing and Clutches The reversing reduction gears were supplied by Falk Corporation and are of the divided train, double reduction type located forward of the gas turbines with the drive to the propellers led underneath the engines. The port reversing gear is shown diagramatically in Figure A.5. The input from the power turbine is taken into two pairs of first reduction gears which turn at 800 rpm when the turbine speed is 3,600 rpm. Quill shafts from one pair of first reduc-

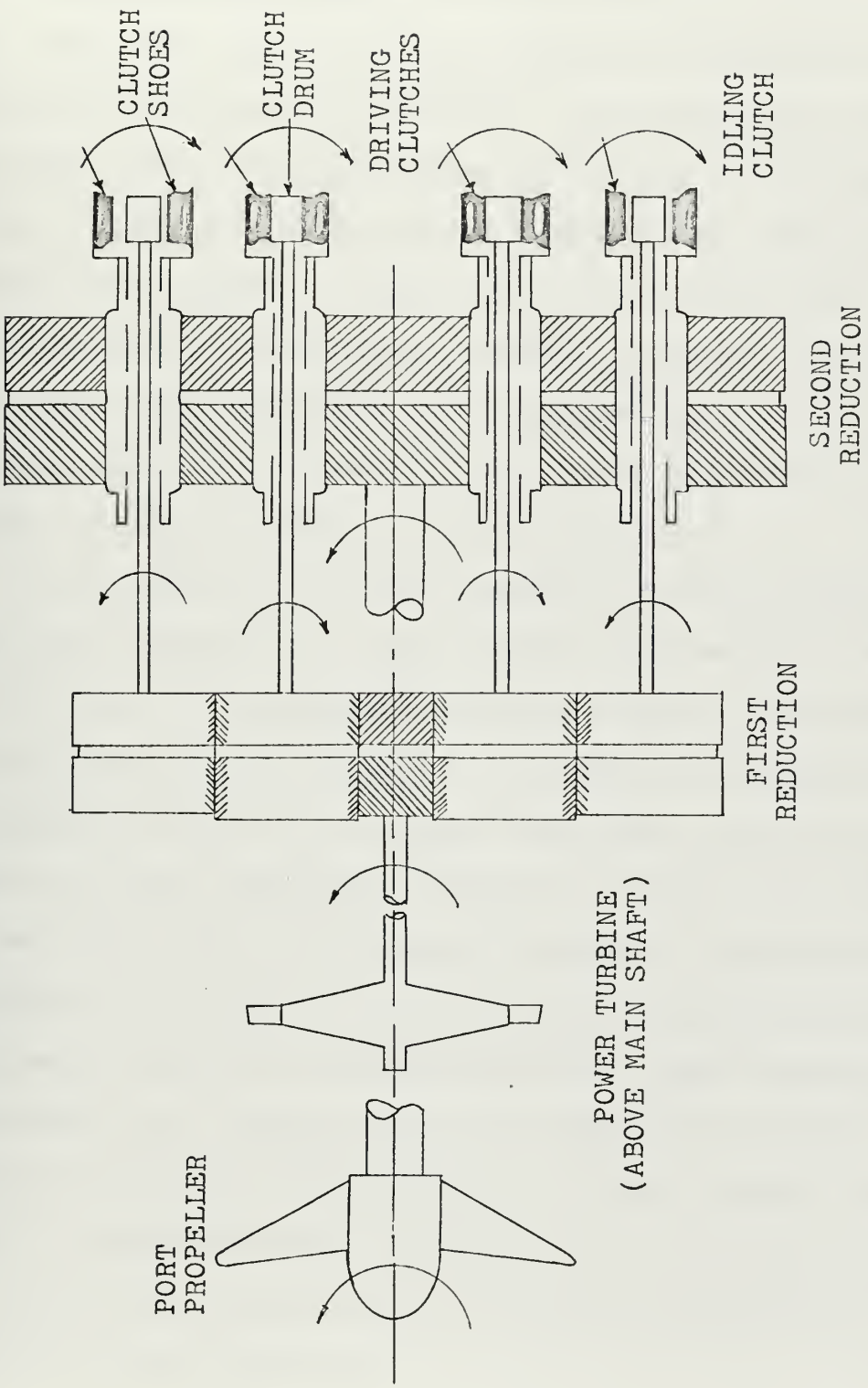

FIG. A.5 Diagram of Port Reversing Gear in Callaghan (59)

tion gears drive back to the main reduction gear via a pair of clutch-coupled second reduction pinions. When these are turning in the ahead direction, the second pair of first reduction gears turns its respective quill shafts in the reverse direction but in the unloaded condition. To reverse the rotation of the output shaft the gas turbine is brought to an idling condition, the ahead clutches are disengaged and the reverse clutches are engaged. In the port side gear box, the inner pair of reduction pinions are coupled to the main gear in the ahead condition; the outer pair of pinions are used in the starboard gear box so that the propellers are both outboard turning. Overall reduction ratio is 26.7:1.

The clutches are Airflex pneumatic type with asbestos faced shoes mounted on a torus shaped gland and are designed to absorb the heat generated during a reversing operation as well as transmit the torque. This method of reversing owes its success to the fact that the rotational inertia of the gas turbine and high speed gear elements is greater than that of the low speed gears, shafting and propeller by enough margin to overcome the counter propeller torque experienced while the ship coasts during a reversing maneuver. When maneuvering at a low speed, the clutches must be slipped continuously to achieve the desired propeller rpm. At these speeds, very little power is transmitted and it has been found that the clutch can be slipped continuously without causing overheating or noticeable wear of the clutches.

Lubricating System Each of the gas turbines (FT4's) have two lubrication systems, one for the gas generator and one for the power turbine, employing special high temperature synthetic oil. This synthetic oil is cooled in heat exchangers using the main reduction gear mineral oil as a coolant. The reduction gear oil is then cooled by sea water.

Oil vapor from the gears and gas turbines must be carefully controlled to prevent its deposition on the clutch surfaces. The rotating clutches tend to centrifuge oil from the cooling air passing through the clutch cases and this oil deposit could be a hazard to clutch reliability. Substantial corrective modifications to improve the venting system of the ship were made after early service experience demonstrated existence of this problem.

Air Supply and Exhaust System Separate ductwork is installed for each gas turbine to preclude the possibility of induced circulation when one turbine is secured. The relatively straight runs of ductwork are located in structural casings rising from the deck above the engine room to the top of the deck house. Intake air enters the inlet duct through weather screen and plenum on the aft side of the deck house about 67 feet above the water line. The combustion air passes through a multiple moisture separator system incorporating hot air bleed from the gas turbines to permit deicing the separators if required. Intake air then moves downward through two stages of inlet

silencers of the splitter type and enters a plenum at the inlet end of the gas turbine. Further anti-icing protection is provided by resistance heaters in the inlet bellmouth and compressor bleed air for the inlet guide vanes and nose cone. The exhaust gas passes through a single silencer and exhausts from the stacks at a height sufficient to prevent recirculation into the air intakes.

Control System The ship employs a centralized engine room control system utilizing a control console located in the auxilliary machinery space. The engines are started, controlled and monitored from this position. The single lever throttle/clutch controls are duplicated on the bridge to permit the engines to be operated from there also. Maneuvering control is achieved by translation and programming of a pneumatic signal from the engine control lever to the proper combination of engine throttle sitting and clutch air pressure for the ahead or astern clutches.

Automatic shutdown of each gas turbine is provided for when any of the following conditions are detected:

1) flame failure
2) low L.O. pressure on gas generator or free turbine
3) overspeed on free turbine
4) high L.O. inlet temperature on gas generator or free turbine

5) high exhaust temperature from gas generator turbine.

During operation many shutdowns have occurred because of instrumentation failures and it is felt (10) that engine shutdown requirements should be minimized. Presently the U.S. Coast Guard requires automatic shutdown only for overspeed and low lubricating oil pressure.

A.5. CANADIAN DDH-280 CLASS (69, 70)

SHIP

Displacement	4,200 tons
Length between perpendiculars	398 ft.
Beam	50 ft.
Speed	27 kts.
Sea trials planned	Mid 1971

MAIN PROPULSION SYSTEM

The COGOG propulsion system consists of two main gas turbine engines of 25,000 hp each or two cruise gas turbine engines of 3,700 hp each driving two controllable reversible pitch propellers through reduction gears with clutches.

Both gear boxes and a raft bearing all four engines are grouped into a relatively rigid assembly which floats as a unit on rubber vibration attenuating mounts which are mounted on the ship's support structure. The output drive from the gear box to the propeller shaft is through a "rubber tire" coupling designed to accomodate misalignment and provide vibration attenuation to the shafting. The machinery space layout is shown in Figure A.6.

Engines The main gas turbines are Pratt & Whitney FT4A-2 and the cruise gas turbines are Pratt & Whitney FT12A-3. The free power turbines for each shaft on both the cruise and main

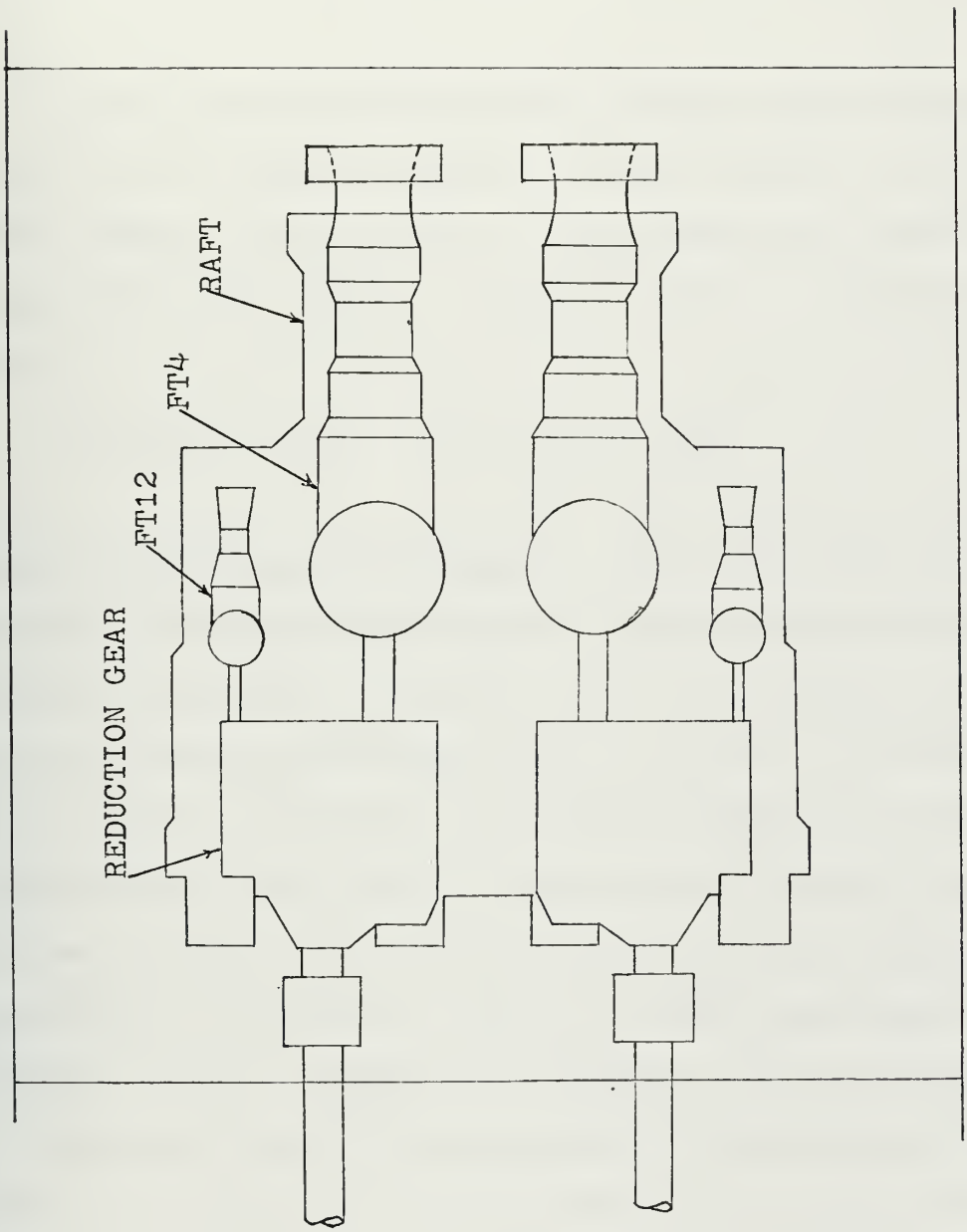

FIG. A.6 DDH-280 Machinery Space Layout (70).

engines are designed to turn in opposite directions resulting in completely symmetrical gearing. Because the only connection between the power turbines and the gas generators is a gas coupling, all the gas generators rotate in their normal direction.

Engine starting and motoring during engine washing is accomplished by using a hydraulic system supplied by New York Air Brake Company and is sized to start both main engines simultaneously. The hydraulic starting pumps are driven by electric motors.

Both engines use marine diesel fuel.

Reduction Gearing and Clutches The reduction gearing was designed and manufactured by the Maag Gear Wheel Company of Zurich, Switzerland. The FT4 drive is a locked train arrangement with overall reduction ratio of 15.6:1. The FT12 drive used a double reduction articulated single train drive with overall reduction of 68:1. The gears are single helical, hardened and ground. All FT4 gears are carburized except the main gear which is nitrided. The FT12 primary gear wheels are also nitrided and the primary and secondary pinions are carburized.

Both FT4 and FT12 clutches are of the same size (SSS size 160T). Both clutches are located on the aft face of the gear box to provide for accessability.

The FT12 clutch controls the drive from the primary gear to the secondary pinion drive quill. When this clutch is

disengaged, rotation of the main gear will rotate only the secondary pinion of the FT12. The FT4 clutch controls the drive from the input quill to the primary FT4 pinion. This location avoids the need for two clutches on the locked train arrangement but does cause all the FT4 gears to rotate whenever the main gear rotates.

Propellers The inward turning five-bladed controllable pitch propellers were designed by Lips N.V. This design uses an all-mechanical propeller hub with a long push rod transmitting pitch holding and changing forces through the shaft bore from the hydraulic actuator. The hydraulic actuator is a double acting ram in an enlarged section of the shaft inboard of the sternseal. Within the propeller hub, mounted on the push rod, is a 5-sided yoke with 5 eccentric pins. Each pin carries a rectangular block which engages a slot in the inner face of the blade foot. Axial movement of the push rod and yoke cause the blade pitch to change.

A separate pitch changing hydraulic system is provided for each shaft line. Each system uses a 50 hp electric motor driven hydraulic pump. A stand-by belt-driven pump is automatically engaged if power is lost. Also port and starboard hydraulic systems are normally cross-connected to provide further redundancy. Oil is transferred from the hydraulic system to the rotating shaft through a co-axial oil transfer sleeve.

This system is capable of completing a pitch change from

full ahead to full astern in less than 20 seconds.

Lubrication System The gas turbine engine synthetic oil system reject heat to the gear box mineral lube oil in engine oil coolers. The mineral oil is then cooled by sea water in the main lube oil coolers. The system is duplicated, port and starboard, with emergency cross connections for redundancy.

Air and Exhaust Ducting Each engine has a separate intake. The FT4's use an intake plenum formed by an enlargement of the bottom end of the down take, while the FT12's use a direct axial inlet fed by a duct curving off from the down take. Each engine's intake makes separate provision for mist eliminators, intake screen, intake silencing splitters and intake silencing lining.

Each engine also has a separate exhaust. All the exhaust ducts are circular to the outlets at the top of the funnel and have expansion joints to accomodate thermal, differential expansion and raft movement in shock and roll conditions.

Each of the four engines is covered with an individual air cooled, insulated sound attenuated enclosure. Both the FT4 and FT12 gas generators can be removed through the FT4 inlet ducting.

Control System The control system includes a bridge console for one man operation of steering and propulsion power. A main control console in the machinery control room provides another

control position with complete monitoring facilities including automatic scanning of plant parameters, warning displays and automatic data logging devices. Single lever control is provided for each shaft line with automatic sequencing of machinery plant functions including engine start up, shutdown and changeover.

Testing A complete port shaft line of machinery was shore tested at the U.S. Naval Ship Engineering Center, Philadelphia Division prior to ship installation.

B.1. GE MS 5272 HEAVY DUTY MARINE GAS TURBINE (71)

The GE MS 5272 heavy duty marine gas turbine is a two shaft engine with variable angle load turbine nozzles. It can be supplied as either simple cycle or regenerative cycle.

Cycle Arrangement The engine consists of a 16 stage axial flow compressor, combustor section, a single stage high pressure turbine connected to the compressor and the tandem single stage low pressure (load) turbine.

The combustion system is composed of twelve 10 inch diameter chambers located around the outside of the compressor casing and enclosed in a cylindrical pressure shell (combustion wrapper). Flow shields around each chamber force the air to flow around the outside of the chamber in a direction opposite to the internal flow.

The combustion wrapper configuration rather than use of individual outer cans for each chamber is dictated by the need to convey compressor discharge air out to the regenerator and back to the combustors.

Each combustion chamber discharges through a separate sheet metal transition piece to the first stage turbine nozzle. In the regenerative cycle arrangement there is a seal at the inlet end of each transition piece that prevents compressor discharge air from flowing directly into the combustor inlet space. For simple cycle units, this seal is removed.

Bearings The gas generator set rotor is supported by two pressure-lubricated, elliptical journal bearings. The gas generator thrust is carried by a self-equalizing, tilting pad bearing located in the compressor inlet housing.

The load turbine rotor is supported by two pressure-lubricated, tilting pad journal bearings. The load rotor thrust is taken by a tilting pad bearing located at the outboard end of the load shaft.

Stator Structure Starting at the compressor inlet, the stator structure consists of the compressor casing back to the beginning of the discharge diffuser. At this point the compressor discharge casing branches into eight struts, located between combustion chambers. These struts connect to the forward end of the turbine shell (casing) which extends to downstream of the load turbine nozzle. Starting at the load turbine bucket inlet, the exhaust frame consists of a drum outside the exhaust diffuser, connected by six radial struts to an inner drum. The inner drum connects to the outboard load turbine bearing housing.

The engine is supported from its base at the compressor inlet casing and at the outboard load turbine bearing housing.

The combustion wrapper is designed strictly as a gas containing member and does not contribute to the stator structural strength. The wrapper and all casings are flanged at the horizontal centerline to permit convenient disassembly.

Compressor Rotor The compressor rotor construction consists of individual rotor disks for each stage. Blades are affixed to the disks by dovetails aligned with the air-foil root tangent line. Through-bolts connect the rotor disks to the forward and aft subshafts.

Turbine The high pressure turbine rated speed is 5,100 rpm. The load turbine rated speed is 4,670 rpm, with capability of continuous operation at up to 4,900 rpm.

The first stage nozzle consists of twelve precision-cast segments. Each segment contains three vanes. Trailing edge cooling is obtained by compressor discharge air that passes in the vane core and thence through holes onto the vane pressure surface immediately upstream of the trailing edge.

Both stages utilize precision-cast, long-shank buckets. The long-shank feature shields the wheel rim and bucket root fastening from the high temperature in the main gas stream, and adds vibration damping. The first stage bucket vane is hollowed out to reduce the centrifugal load and also to reduce the transient thermal stresses. The second stage bucket uses a tip shroud to provide vibration damping and to mount seal teeth that reduce the tip leakage flow.

The variable second stage nozzle consists of 32 precision-cast nozzle vanes mounted on shafts that extend radially through the turbine casing. Each shaft carries a lever arm that connects to the control ring which rotates around the casing to vary the nozzle throat area. The control ring is actuated by a hydraulic

cylinder operated by the control system.

Marinization Materials throughout the engine have been selected on the basis of their ability to withstand the marine environment. Table B.1. gives some of the material used in a marinized unit. Built-in water washing systems will provide easy cleaning of the compressor and turbine gas paths during port shutdown periods.

Controls The engine will utilize an analog and digital gas turbine control, protection and sequential system with a built-in power supply. The total system is comprised of four basic subsystems: (a) the Control System for normal running operation, (b) the Protection System for an independent back-up of the Control System, (c) the Sequential System which provides automatic startup and shutdown, and (d) the Power Supply System which makes the overall system independent of external power.

Redundancy is applied throughout the total system to assure reliability and fail-safe operation. The Control System is designed to be "operation-continue" with backup provided by the alternate subsystems. For example, with operation on temperature control, the system is backed up by the speed control loop, and vice versa.

An inductor alternator mounted on the gas turbine compressor shaft provides the complete electrical power for the control and operation of the turbine, after the engine is started.

TABLE B.1. MATERIALS FOR GE MS 5272

Item	Material
Inlet Guide Vanes	316LSS or NiCd plated 403 SS
Compressor Rotor Blades	NiCd plated 403SS
Compressor Stator Blades	NiCd plated 403SS
Compressor Wheels	Epoxy painted 4140 steel
Turbine Wheels	A286/M152
Turbine Shrouds	310SS
First Stage Nozzle	FSX414
Second Stage Nozzle	N155
Regenerator	Carbon steel
Bearing Oil Seals	5052 A1
Turbine Blades- Stage 1	I738
Turbine Blades - Stage 2	U500
Combustion Liners	RA333

During starting, an outside source of either 115-v, 60-Hz a-c, or 125-v d-c power is required.

The engine control system when combined with COS (Central Operations System) permits complete operation of the total propulsion system from the bridge.

Accessory System All of the powered accessories required for running the engine are shaft driven from an accessory gear which is coupled to the forward compressor subshaft. These include the main lube oil pump, the fuel oil pump, air compressor for fuel oil atomization, the control oil pump, and cooling water pump.

The same lubrication oil system supplies the engine bearings, main reduction gear, and accessory.

The starting means driving through the accessory gear can be either an electric motor, steam turbine, or diesel engine.

The engine and all accessories are base mounted, greatly reducing the elapsed time and effort of shipyard installation. Base mounting also permits factory operation and testing of the complete engine and its accessory system prior to installation in the ship, saving shipyard check-out time.

Performance The regenerative cycle performance on residual fuel is given in Table B.2. The output, SFC and thermal efficiency are supposed to be guarantee values, and hence may be conservative compared to the expected performance.

TABLE B.2. PERFORMANCE OF GE MS 5272R ON RESIDUAL FUEL

Air Flow	Lb/Sec	249
Compressor Ratio	-	8.2
Firing Temperature	F	1,700
Exhaust Temperature	F	955
Stack Temperature	F	682
Engine Shaft Output	HP	27,800
Specific Fuel Consumption	Lb/HP-Hr	.44
Thermal Efficiency (LHV)	%	33

Conditions: 14.7 psia, 70F, 3" H_2O inlet drop and 5" H_2O exit drop, 17,500 Btu/Lb LHV

On distillate fuel the TIT can be increased to 1750° F, increasing the output to 29,300 hp and the thermal efficiency to 33.8 per cent.

B.2. ROLLS-ROYCE OLYMPUS MARINE GAS TURBINE (20)

The engine consists of a gas generator which is a modified version of an established aircraft jet engine supplying high pressure hot gas to a specially designed power turbine which converts the gas energy to shaft horsepower.

Gas Generator The gas generator is developed from the Olympus 201 jet engine which is used in the Vulcan aircraft and is basically a straight-flow double-compound (two-spool) unit. It employs two separate axial flow turbines. The combustion system comprises eight flame tubes each with a burner contained within an annular casing.

The low-pressure (L.P.) and high-pressure (H.P.) compressors are arranged in tandem with the low-pressure compressor supplying air to the high-pressure compressor. The low-pressure compressor is driven by the second stage (rear) turbine and the high-pressure compressor is driven by the first stage (front) turbine giving an overall compression ratio of 10:1 with a mass flow of 230 lb/s maximum rating.

The main components of the engine are as follows:

1) Air Intake Casing - This is an aluminum alloy casing which carries the low-pressure compressor front roller journal bearing, the nose fairing and the inlet guide vanes.

2) Low-Pressure Compressor - The low-pressure compressor is a five stage axial flow unit and consists of an aluminum

casing, cast in two halves, which houses the four rows of stainless steel stator blading in dovetail section grooves machined within the casing diameter.

The rotor assembly is of disc type construction carrying the five rows of rotor blades and the whole assembly of discs and blades is made from stainless steel. The blades are retained in the discs by means of convertional fir-tree root fixings.

The compressor drive shaft is secured by its integral flange to the rear of the rotor assembly. A bearing seal positioned to the rear of the flange is followed by a matched pair of thrust ball bearings. The latter supports the rear end of the compressor rotor within the intermediate casing.

3) Intermediate Casing - Fitted between the low-pressure and high-pressure compressor is a cast aluminum intermediate casing which houses the low-pressure exit vanes and high-pressure inlet guide vanes.

The center section of the casing supports the low-pressure compressor rear bearing and the diaphragm at the rear of the casing supports the high-pressure compressor front roller bearing.

The attachment faces for the auxiliaries are arranged around the outer casing and embody drive housings in two groups; i.e., the low-pressure and high-pressure drives. The low- pressure group comprises the following drives:

a) low-pressure tachometer generator

b) low-pressure driven fuel pump.

The high-pressure group comprises the following drives:

a) high-pressure driven fuel pump

b) gas generator main oil pump and four scavenge pumps

c) high-pressure tachometer generator

d) starter drive.

4) High-Pressure Compressor - The high-pressure compressor is a seven stage axial flow compressor manufactured entirely from stainless steel. Apart from the fact that the compressor casing is made in halves from stainless steel, the construction is very similar to that of the low-pressure compressor, the rotor being of disc construction with blades mounted in fir-tree roots.

The rotor is supported on its front end by the front rotor shaft which is screwed to the first and second stage discs. This shaft is located in the front roller bearing in the intermediate casing.

The rotor is supported on it's after end of the rear rotor center shaft which is carried on a matched pair of thrust ball bearings. This shaft also carries the compressor drive coupling.

An air supply is provided from the third stage of this compressor to supply cooling air for the rear face of the second stage turbine and for pressurizing bearing seals.

5) Delivery Casing - The delivery casing fabricated from stainless steel is interposed between the high-pressure casing and the combustion chamber outer casing and carries the matched

pair of thrust ball bearings of the high-pressure compressor.

6) Main Bearings - The gas generator rotating assembly is supported by seven main bearings, the positions of which are as follows:

i) the low-pressure compressor front roller bearing is housed in the rear of the air intake casing;

ii) the low-pressure compressor rear thrust double ball bearing is housed in the center section of the intermediate casing;

iii) the high-pressure compressor front roller bearing is retained in the rear diaphragm of the intermediate casing;

iv) the high-pressure compressor rear thrust double ball bearing is supported in a housing in front of the coupling chamber unit;

v) the inter-shaft roller bearing is fixed between the low-pressure and high-pressure compressor couplings;

vi) the first stage turbine roller bearing is housed at the rear of the turbine inner drum;

vii) the second stage turbine roller bearing is housed in the exhaust annulus.

7) Combustion Chamber Outer Casing - The steel casing of the combustion chamber comprises top and bottom halves secured at the horizontal center line flanges with nuts and bolts.

The casing is fitted between the delivery casing rear flange and the low-pressure turbine casing, with the turbine stator supporting ring interposed.

8) Flame Tubes and Turbine Entry Duct Unit - Eight flame tubes are assembled around the annulus formed between the combustion chamber outer casing and turbine inner drum. If necessary, the flame tubes may be removed and replaced without removing the gas generator.

9) Turbine Assembly - The turbine assembly comprises the high-pressure turbine bearing support housing, the high-pressure turbine rotor and the low-pressure turbine rotor.

The bearing housing is supported by a diaphragm unit which is secured at it's front end to the rear face of the combustion chamber inner casing. The rear end of this unit accomodates the turbine bearing and housing, the stationary portion of the turbine bearing seal, the stator support cone and the high-pressure turbine stators. Lubrication for the bearing is by means of an oil-jet assembly which is provided in the housing.

The high-pressure turbine disc is bolted to the large flange at the rear of the hollow turbine shaft, and forward of this flange are the front and rear seals. The front end of the shaft accommodates the compressor driving coupling assembly.

The hollow low-pressure turbine shaft passes through the bore of the high-pressure turbine shaft and a seal at its front end prevents hot air from the turbine passing between the shafts to the coupling chamber. The front end of the shaft also accom-

modates the turbine coupling which is secured on splines.

The high-pressure and low-pressure turbine blades are impulse/reaction type, shrouded at the tips. The root of each blade is of the fir-tree form, which is located axially by a projection piece at its forward end and a locking tab at its rear end. The high pressure stator and rotor blading are of X.40 and Nimonic 105 respectively and are "pack aluminized" to increase corrosion resistance. The low-pressure turbine bearing together with the relevant seal fitted between the bearing and disc, is secured to the wheel hub by a ring nut.

10) Exhaust Annulus - The exhaust annulus is mounted to the rear face of the low-pressure turbine casing and consists of an inner and outer steel ring connected by eight radial hollow vanes. At the front end of the annulus is a diaphragm which supports the low-pressure turbine shaft roller bearing and housing.

TM.1 Power Turbine The whole unit is carried on a heavy steel base plate which is mounted off the ship's structure at four points.

Separately mounted on the base plate are:

a) the turbine stator system and inter-turbine duct and exhaust volute

b) the steel pedestal which carries the turbine rotor shaft.

The turbine stator system is carried off a steel support ring, integral with the base plate by means of a segmental cone.

The stator casing is a centri-spun stainless steel casting split on the horizontal center line to facilitate fitting, removal and inspection of the 56 forged Ni.80 stator blades.

The single stage rotor consists of a row of 71 Ni.80A forged blades attached to a vacuum-melted forged disc. The blades are attached to the disc by conventional fir-tree root fixings.

The bladed disc is located on a stub shaft by "Hirth" couplings centralizing the disc and permitting differential growth. This assembly is secured by a single nut at the forward end of the stub shaft. The main shaft is bolted to the stub shaft and supported by two substantial journal bearings housed in the bearing pedestal. The pedestal is designed to contain the axial-thrust loads from the double-acting thrust bearing which is located in the pedestal. Each bearing can be examined individually by removing the easily accessible bolts in the pedistal covers.

The main shaft also carries the overspeed trip plate which operates the overspeed trip mechanism mounted on the pedestal. The trip plate is designed to operate by centrifugal force when the turbine shaft exceeds its maximum design speed by ten per cent. The trip ring triggers a mechanism which closes the high-speed shut-off cock, thus stopping the supply of fuel to the gas generator. This mechanism is in fact the ultimate safeguard against power turbine overspeeding and it is entirely independent of any accessory drives or other governors in the main fuel-control system.

After leaving the power turbine, the exhaust gas is diffused and then directed into the exhaust volute by cascade vanes. A flexible bellows attached to the exhaust volute flange caters for deflections imposed through thermal distortion or hull movements and prevents uptake loads being transmitted to the power turbine..

The gas generator itself is carried off the front of the power turbine assembly by means of two tubular cantilever structures each mounted on two ball joints. A bellows joint is provided in the duct to the power turbine and the gas generator and the cantilever structures are arranged so that the deflections of the bellows under shock load are minimized. Due to the resilience of this structure, shock accelerations experienced by the gas generator are lower than those arriving at the power turbine.

This arrangement simplifies the removal of a gas generator for repair as the tubular support frames can be swung sideways clear of the gas generator, thus allowing the gas generator to be lowered on to a suitable trolley. Replacement of the gas generator is simple as no alignment problems are involved, the only connection with the power turbine assembly being the bellows joint.

Controls and Fuel System The fuel-control system for the marine Olympus engine involves two separate methods of controlling the fuel flow; firstly by means of a throttle, and secondly

from the speed of the power turbine. In addition, safety devices are provided which prevent the power turbine or either of the gas generator rotors being damaged by overspeeding and which prevent the gas generator being damaged by excessive temperature.

Performance The performance of the marine Olympus TM1 engine at an atmospheric temperature of 59° F and pressure of 14.7 lb/in^2, without allowance for ship ducting losses is as shown below:

	BHP	SFC	Maximum Cycle Temperature
Maximum Continuous	24,000	.50 lb/hp-hr	1620° F
Normal	19,000	.53 lb/hp-hr	1475° F

B.3. GE LM 2500 (21, 72)

The LM 2500 basically is the TF39 turbo fan jet engine with the front fan and shaft removed and an aft-extending power shaft added to the power turbine. Some material changes were made to improve corrosion protection from contaminants in the air and in the fuel.

The LM 2500 is a dual-rotor gas turbine with a 16 stage, single spool, variable-stator compressor, an annular combustor, a two stage air-cooled gas generator turbine and a six stage power turbine. The power turbine is aerodynamically coupled to the gas generator. Shaft power is extracted from the power turbine by the aft-extending coupling.

The LM 2500 gas turbine consumes 135 pounds of air per second, has a turbine inlet temperature of about 2150° F, a pressure ratio of 16.8:1, an exhaust gas temperature of about 980° F and is max-rated at approximately 25,500 shaft horsepower at 100° F. A compact engine, its length is only 20 feet and its weight is approximately 10,500 pounds.

Corrosion Protection In the LM 2500, the cold section parts are made from materials inherently corrosion-resistant (Titanium, Inco 718, A286 and 17-4PH). In the hot section, turbine vanes and blades have an aluminized diffusion coating. In addition, a thin layer of relatively cool, clean air is applied around the airfoils of the first stage vanes and blades. This

film of cool air provides a buffer which keeps the contaminants away from the airfoil to some degree.

Compressor The compressor is a 16 stage axial compressor with 6 rows of variable stator blades followed by 10 rows of fixed stator blades. The pressure rise per stage is greater than that in earlier aircraft derivative engines. It is claimed that this is the result of higher tip speeds and higher radius ratios.

Combustor The annular combustor has 30 fuel nozzles. This number of fuel nozzles provides a good fuel spray pattern and reduces variations in gas temperature. The design provides careful control over cooling air, protecting the walls of the liner so that hot spots are virtually eliminated. These features permit a higher temperature rise through the combustor, while maintaining cooler combustor liner walls.

Turbine The highest temperature in the engine is at the entrance to the high-pressure turbine. Although hollow air-cooled turbine blades and vanes have been used on earlier engines, the LM 2500 makes extensive use of film cooling, impingement cooling and convection cooling so that metal temperatures are actually lower than in earlier engines, while gas temperatures are several hundred degrees higher. With a special process, small, accurately-located holes can be placed where

needed in the airfoil to give optimum film or convective cooling. While these holes are relatively small and the amount of air passing through them is carefully controlled, it is claimed that they do not become clogged in operation.

Power Turbine The power turbine of the LM 2500 has six stages, a number higher than usually associated with first-generation machines. The higher number of stages gives higher efficiencies at smaller diameters and lower turbine speeds. No special cooling is needed for this component, since the temperature levels are down.

Performance The maximum expected performance for the LM 2500 at 14.7 psia, 100° F inlet conditions with 3" H_2O inlet and 5" H_2O exhaust pressure drop is given below:

	BHP	SFC	Turbine Inlet Temperature
Maximum Continuous	25,500	.39 lb/hp-hr	2150° F
Normal	22,200	.41 lb/hp-hr	-

C. POLYTROPIC EFFICIENCY

Most often in giving an efficiency of an expansion or a compression process, isentropic efficiency is used, that is, for a compression process for example, the ratio of the work required in an isentropic process in compressing a gas from specified inlet conditions to a specified outlet pressure to that that would be required in the actual process in compressing the gas from the same inlet conditions to the same exit pressure. The trouble with using isentropic efficiencies in discussing the state of the art in trubines or compressors is that for a multi-stage compression or expansion even if all isentropic stage efficiencies are the same, the overall isentropic efficiency for the process will not be equal to the stage efficiency and will instead vary with pressure ratio. The effect of the overall pressure ratio on the relationship between the individual stage efficiency and the overall efficiency of the process can be seen by visualizing the process on an enthalpy-entropy diagram. (73).

As the actual compression is not isentropic, the starting point for each elemental stage (after the first) will be at a higher level of entropy than the starting point for the whole process. Thus, since the vertical distance between two constant pressure lines increases with entropy, the isentropic enthalpy rise for the elemental stage is greater than that for the corresponding stage in a frictionless compression; this

effect is sometimes known as preheating. Hence, the sum of the isentropic enthalpy rises in all of the elemental stages, making up the complete compression, $\sum \Delta h_{is}$, will be greater than the single overall enthalpy rise which would result from an overall frictionless compression, Δh_{is}, and this effect is magnified as the pressure ratio increases. Now, since the actual enthalpy rise, Δh, is the same in both cases and the overall efficiency is given by dividing Δh_{is} by Δh and the elemental stage efficiency by $\sum \Delta h_{is}$ by Δh, it follows that the overall efficiency will be lower than the elemental stage efficiency and will decrease with increased pressure ratio.

A similar argument applies to an expansion process occurring in a multi-stage turbine except that in this case the overall efficiency will be greater than the elemental stage efficiency and increases with increasing pressure ratio. In this case the gain in efficiency is due to a reheating effect which corresponds to the preheating in the compression process.

In order to have an efficiency which is not a function of overall pressure ratio and is therefore more convenient to use in general cycle performance predictions, a "small stage" or polytropic efficiency is defined as the limit of isentropic efficiency as the pressure ratio goes to zero. The overall isentropic efficiencies for compression, η_C, and expansion, η_T, can be shown to be related to the polytropic efficiency for compression, η_{P_C}, and for expansion, η_{P_T}, in the following manner (for perfect gases): (22)

$$\eta_c = \frac{r^{\left(\frac{\gamma-1}{\gamma}\right)} - 1}{r^{\left(\frac{\gamma-1}{\eta_{P_c}\gamma}\right)} - 1}$$

$$\eta_T = \frac{1 - (1/r)^{\eta_{P_T}\left(\frac{\gamma-1}{\gamma}\right)}}{1 - (1/r)^{\left(\frac{\gamma-1}{\gamma}\right)}}$$

In discussing the state of the art of compressor or turbine design, therefore, it is usual to use polytropic efficiencies.

D. SURVEY OF AUTHORITIES IN GAS TURBINE AND MARINE ENGINEERING FIELD

In order to obtain the views of a large number of authorities in the gas turbine and marine engineering field, a survey was designed to provide maximum information with a minimum amount of effort on the part of each person surveyed. This survey consisted of a number of conclusions or predictions (a total of twelve statements) concerning various aspects of marine gas turbine propulsion. For each statement, the person being surveyed was asked to indicate whether he agreed, agreed in part, disagreed, or had no information concerning the statement. Comments concerning the statements or marine gas turbine propulsion in general were encouraged and many were received.

Individuals, not firms or agencies, were surveyed. However, the individuals surveyed are somewhat arbitrarily divided into categories depending upon the nature of the firm or agency with which the individual is associated. The main categories are users and manufacturers. The user category includes individuals associated with naval architecture and marine engineering firms, shipbuilders, U.S. Navy, Royal Canadian Navy, U.S. Coast Guard, and the U.S. Maritime Administration. The manufacturer category includes manufacturers of both aircraft and heavy duty type gas turbine engines. In addition to these, a third category, termed "others" includes a few authorities who do not appear to fit into either of the two main categories. Although it is understood that the views of an individual does not necessarily

represent the views of the firm or agency with which he is associated, it is felt that his views are influenced by the nature of his work, so it is useful to have the authorities divided into different categories.

The results of the survey including many of the comments received are presented below.

1. The naval field for aircraft derivative marine gas turbines is firmly established and in the future most non-nuclear warships other than carriers will be propelled entirely by these gas turbines.

	Agree	Agree in Part	Disagree	No Information
Users	45.5%	36.4%	9.1%	9.1%
Manuf.	60	30	10	-
Others	-	100	-	-
All	47.8	39.2	8.7	4.3

Comments:

Users

1. Possibly true in numbers but not necessarily by types. The gas turbine has many advantages but also limitations. There is much room for development of other propulsion systems.

2. Industrial gas turbines may prove more economical to operate. GE is devoting a good deal of time to developing them for marine use.

3. CODOG or CODAG can not be ruled out for all war-

ships. If large endurance at low speeds is required, then a CODOG plant may be more suitable.

4. For combatant ships this appears to be true, because of the improved performance of second generation engines (LM 2500) and the conversion of the fuel system from NSFO to Std. Navy Distillate. (U.S.)

Manufacturers

1. Gas turbines designed for specific power ranges can be economically competitive with diesel and steam propulsion. The size and weight of the gas turbine provides a definite advantage specifically for military craft.

2. Not firmly established. Small size gas turbines, 2,000 - 10,000 hp, not yet available with desired SFC and life.

3. Exceptions to above - small vessels, such as minesweepers where high speed is not important.

4. There will be a predominance of aircraft derivative units in the fast deployment area but surely there must also be some committment to economy and the use of cruise arrangements.

Others

1. Expect to see both diesel and gas turbines.

2. It appears that the naval use of aircraft derivative gas turbines in the marine field is well established. However, can not say that the future non-nuclear warships excluding carriers, will be propelled entirely by this prime mover. Only recently has the U.S. Navy decided on gas turbine propulsion for destroyers.

2. At present in the merchant ship field the gas turbine power plant seems suited only for those ships designed for high speed, high utilization factor and maximum percentage of cargo space to total ship volume such as container and roll on/roll off ships.

	Agree	Agree in Part	Disagree	No Information
Users	36.4%	18.1%	36.4%	9.1%
Manuf.	40	50	10	-
Others	-	50	50	-
All	34.8	34.8	26.1	4.3

Comments:

Users

1. Economic advantages for merchant ships are very questionable.

2. The aircraft gas turbine is best suited for high utilization ships. The industrial engine will be adapted to general cargo ships and tankers.

3. An industrial type gas turbine, when adapted for marine use may be competitive with steam or diesel for other kinds of logistic ships.

4. Fuel costs and what appears to be high maintenance costs for the aircraft derivative gas turbine are factors which militate against the use of these power plants in ships in which high speed and maximized cargo spaces are not required. The industrial gas turbine may become more useful for a broader

spectrum of ships than the aircraft derivative type; however, more practical experience is needed with the industrial gas turbine than is currently available.

5. Future merchant marine propulsion plants in this country (U.S.): the industrial g.t. should make the first real inroad into the conventional steam plant but that will not occur for several years, even though today it is economically attractive. Aircraft g.t.'s should really be limited to a relatively few installations where the ship is tailored to the particular engine. Since it can not and will not ever burn residual fuels, it is not economically competitive with the industrial g.t., diesel or steam.

Manufacturers

1. True only if the currently available large aircraft derivative gas turbines are considered. It is possible, however, for smaller gas turbines to be competitive in the remainder of the marine field.

Others

1. Most suitable for these, but could change with heavy distillate fuel at lower cost.

2. Would not agree that the gas turbine power plant is suited only for ships designed for high speed, etc. Each ship application must be studied individually and a blanket statement is not in order.

3. Reversing the shaft output is no longer a serious problem in the use of gas turbines for marine propulsion since controllable reversible pitch propellers are now available for most power ranges of interest. (Also reversing reduction gears or hydraulic reversing may be used).

	Agree	Agree in Part	Disagree	No Information
Users	63.6%	9.1%	27.3%	-
Manuf.	70	30	-	-
Others	-	50	50	-
All	69.6	17.4	13.0	-

Comments:

Users

1. Reversing by any of the above methods is practical but has disadvantages and limitations which are generally understated by enthusiasts.

2. More experience is needed to be sure of the reliability of CRP props. Mechanical reverse gears in large power systems are an undesirable complexity.

3. The GTS Wm. M. Callaghan has demonstrated the practicability of reversing reduction gears and worldwide acceptance of CRP propellers, even in the high horsepowers expected from the aircraft derivative gas turbine, has provided an alternate means of shaft reversal.

4. While the controllable pitch propeller will predominate most g.t. plants, the reverse reduction gear offers

the most attractive solution economically.

Manufacturers

1. Many ship operators have accepted the CRP propeller for general utilization. In other applications such as icebreakers and military craft, it is felt to be superior, due to backing power available for maneuvering, crash stop capability, etc.

2. In the 1,000 to 4,000 hp range CRPP still costs more than reverse gears but the gears are extremely large since they are essentially diesel units.

3. The best way is to redesign the power turbine so that it rotates in the opposite direction.

4. Cost must be considered.

5. The reversing method still dictates arrangements of the gas turbine, gas turbines of 60,000 hp are available and ships with these hp are planned. Transmission systems lag behind.

Others

1. These are expensive, though!

2. The controllable reversible propeller is certainly available for even the large power ranges. It is also important to remember that the reverse gear offers many advantages. The Falk reverse gear installed in the GTS Callaghan has been in service for a number of years and, according to information available, has done quite an outstanding job.

4. Research and development work aimed at making the gas turbine a competitive merchant marine propulsion unit should be concentrated on improving the thermal efficiency and overcoming the problem of heavy residual fuel burning.

	Agree	Agree in Part	Disagree	No Information
Users	27.3%	63.6%	9.1%	-
Manuf.	40	50	10	-
Others	-	-	100	-
All	30.4	52.2	17.4	-

Comments:

Users

1. The industrial gas turbines appear to have more adaptability for heavy residual fuels because the heavier blades are less susceptible to corrosion.

2. R & D should be aimed at consistently successful use of heavy distillates in aviation gas turbines and on more reliable firing of treated residual for industrial type gas turbines. Improved thermal efficiency has less economic gain than potential use of cheaper fuels.

3. More work needs to be done with respect to marinization of aircraft type gas turbines, i.e. ability to withstand effects of salt and moisture laden air.

4. For the aircraft derivative gas turbine it appears that the first problem is learning how to burn cheaper fuel (not necessarily residual fuels). At present this is believed to be

more useful than improving the thermal efficiency. While this is an area where improvements can be made, for the foreseeable future ships will have to accept aircraft derivative gas turbines based, primarily, on aircraft R & D where sizable funds are available for this purpose. The GE LM 2500 is currently competitive with all but the most advanced steam cycles; whether these engines will ever accept residual fuels is problematical.

With respect to the industrial type heavy duty gas turbines, thermal efficiencies can be improved by complications in the cycle utilized, and the problem of utilizing residual fuels in these engines does not appear as difficult as in the aircraft derivative gas turbines. On the other hand, there seems to be a tendency on the part of industrial gas turbine users (ashore) to utilize distillates rather than residuals.

Manufacturers

1. Increasing the thermal efficiency of a gas turbine will add complexity, thus reduce the advantages it has over a competitive system. A heat recovery COGAS system is the most desirable means of increasing the thermal efficiency significantly without adding considerable complexity.

The trend toward more stringent pollution regulations in the U.S. will probably reduce the desire to develop systems to burn the "dirtier" heavy residual fuels as is. Since the systems to treat these fuels will require bulky arrangements of tankage for water and waste material, the trend will be rather toward burning cleaner fuels which will not require treatment.

2. Development should continue on turbine materials and/or coatings to resist hot corrosion/corrosive atmosphere associated with marine environment. The ability to use heavy distillate fuel is considered to be a lesser problem.

3. For the types of applications cited in the second statement, a special fuel (heavy distillate) could be produced with sufficient incentive to oil refiners. In any case metals (vanadium, sodium) in fuel will be one of the limiting factors. Thermal efficiencies are ok now with anticipated power ranges.

4. It'll be "many moons" before a gas turbine, especially an aircraft derivative one can burn residual fuel.

5. Not really worthwhile to develop residual fuel burning capability. Most fuel manufacturers would prefer producing low cost atmospheric distillation products with a high end point, eg., 800 - 825° F, for use in gas turbines, etc. The per cent of domestic crude that ends up as residual is about 5%.

6. And in reducing maintenance costs.

7. From the heavy duty gas turbine viewpoint, the following specifics are listed - reversing gas turbine, weight reduction in heat recovery equipment, increase in hp per frame size, deposition reduction, further increase in maintenance time interval and removal of need to treat Bunker "C" fuel.

Others

1. Marine applications can not afford to develop engines at 50 to 200 million per program but must use either aircraft derivatives or heavy duty units. The efficiency of

aircraft derivative (LM 2500) is now at 35% or so, but it must burn No. 2 or heavy distillate. The heavy duty G.T. with regenerator burns No. 6 and is efficient but does not have the advantages of small size and weight.

2. There appears to be no need for research and development to improve the thermal efficiency of the gas turbine in order to make it competitive with other types of propulsion. As to the problems of burning heavy residual fuels, the day may be seen when burning heavy residual fuels will not be permitted purely from the standpoint of air pollution. Further, there may not be any heavy residuals to burn.

5. First cost of the gas turbine suitable for marine propulsion is presently relatively high, apparently because of small numbers in production and the high cost of development expenditure recovery.

	Agree	Agree in Part	Disagree	No Information
Users	9.1%	27.3%	45.4%	18.2%
Manuf.	40	40	20	-
Others	-	-	100	-
All	21.8	30.4	39.1	8.7

Comments:

Users

1. Costs are inherently high for the aircraft type. The statement might be true for the industrial type if data could be put on a comparable basis which is rarely done.

2. The total installed cost of a complete gas turbine machinery installation in many cases will be less than total installed cost of a comparable steam turbine installation.

3. True, development costs may take some time with LM 2500, for instance, but FT4 has high percentage of parts commonality with J75 of which there are many.

4. The aircraft derivative gas turbine is probably slightly less expensive than a comparable steam plant. However, its development has been funded, primarily, by investigations in the aircraft field. It is doubted that any sizable reduction in price would result from a significantly greater use of

these engines, bearing in mind that the production for aircraft far outweighs the number which can be expected for shipboard use.

5. Statement is too sweeping. One of the advantages claimed for marine gas turbines derived from aircraft engines is that development costs have been absorbed by the high production for aircraft. Installation costs can be considerably lower than those for steam plants.

6. At the present time, it is rare that a gas turbine installation (investment cost) should ever cost more than a steam plant. The development cost of industrial gas turbines is primarily borne by the power generation utilities and the aircraft engine by the Defense Department (U.S.).

Manufacturers

1. The high cost of the aircraft derivative gas turbine is also due partially to the high standards which must be met to insure maximum reliability in an aircraft. Also contributing to the high cost of the more efficient gas turbines is the material cost of the hot section and turbine section materials required to resist high temperature corrosion (TIT above 1600^{o} F) in a marine environment.

2. Total system cost may be less relatively and considering ship construction savings it may be further reduced.

3. Also the basic materials are more expensive but last longer. Balance between acquisition cost and total life cost is in favor of the gas turbine.

4. Also precision manufacture is required.

5. Heavy duty gas turbines have been sold for years in direct competition with diesels and steam on a comparative size basis (with aircraft types also) and it is not a complete picture to assess worth or economics solely on acquisition cost of the prime mover.

Others

1. Not true of aircraft derivative nor of standard industrial design, would be true of units or those components, applied strictly to marine use.

2. The total cost of the ship including the propulsion plant must be taken into account, not just the cost of the prime mover alone.

6. The second generation aircraft derivative gas turbines, typified by the GE LM 2500, would be truly competitive in the general merchant ship propulsion field right now using No. 2-GT ASTM fuel if shipowners would band together to negotiate world-wide fuel purchases at a lower price.

	Agree	Agree in Part	Disagree	No Information
Users	-	18.2%	45.6%	36.4%
Manuf.	30%	40	20	10
Others	-	-	-	100
All	13.1	26.1	30.4	30.4

Comments:

Users

1. This statement overlooks many of the problems of merchant ship operation.

2. The same savings would be realized for any propulsion system.

3. It may not be necessary to "band together". In the world fuel market the per cent difference between heavy distillate and residual is steadily decreasing.

4. Because of pricing practices in the oil industry it is questioned as to whether ship owners acting in consort could generate lower prices for fuel suitable for aircraft derivative gas turbines. Also bear in mind that the bulk of new ship construction in the world is powered by diesel engines, having a fuel rate well below the aircraft derivative gas tur-

bines and utilizing residual fuels.

5. It is not thought that such a proposal would necessarily be acceptable to the fuel suppliers.

6. Why would or should the shipowners take such a course? Both the oil companies and shipowners are in business to make as large a profit as possible. When it becomes economical to market a lower priced fuel such as heavy distillate, the oil companies will do so. The U.S. Navy conversion may well cause this in a few years.

Manufacturers

1. The gas turbine in general is now competitive in the marine industry. The choice of propulsion system is dependent upon many factors and as stated in question two the gas turbine is suited for various applications. If fuel prices of the light distillate are reduced, the gas turbine will of course be put in a better position. The marine industry, however, will be very skeptical of high temperature second generation turbines due to the short hot section life. There will be some question as to whether the decrease in fuel consumption will offset the decrease (to about 2,000 hrs.) of the time between overhauls now being demonstrated by second generation turbines.

2. Not aware that this specific fuel would have to be used.

3. Ok on negotiating fuel prices but aircraft engines should be truly modified (i.e. sleeve type bearings, heavy discs, seals, etc.)

4. Fuel availability and quality around the world is too diverse and different to be able to have a common specification and price.

5. Would probably be competitive in fuel costs but how about other elements of operating costs.

6. Feel sure the manufacturers can prove economics of certain types of installations now and it is assumed that recent contracts ("Euroliner", for instance) must be economically sound.

Others

1. U.S. railroads each buy 50,000,000 gal/year of No. 2 oil of their own specification at 8.5¢/gal. (This is heavier than Std. ASTM No. 2). The new heavy distillates are priced between No. 2 and No. 6 and may be economically attractive. (These are waxy fuels that are heated like No. 6 to be handled and burned but have no ash or sulphur.)

2. Again, there are other factors to consider in the overall ship besides fuel cost. It may be rather difficult to "organize" lower fuel prices.

7. The only practical method of burning residual fuels in gas turbines in the near future is by pretreatment of the fuel (usually water washing followed by addition of chemical inhibitors) and not be other schemes such as combustion at or below the stoichiometric air/fuel ratio or by allowing an equilibrium thickness of ash to deposit on the turbine blades.

	Agree	Agree in Part	Disagree	No Information
Users	63.6%	18.2%	-	18.2%
Manuf.	40	20	20%	20
Others	100	-	-	-
All	56.5	17.4	8.7	17.4

Comments:

Users

1. This appears to be true for the near future but might not continue to be true.

2. Have heard that one foreign company is attempting to burn residual fuels in gas turbines by first gasifying the fuel. If this is practical, it would seem to open up a whole new area of residual use in these engines.

3. The treatment suggested is not necessarily adequate.

4. And this really only applies to industrial G.T.'s. It is very unlikely that aircraft G.T.'s will ever burn any fuel worse than Std. Navy Dist. and even that will reduce overhaul cycles and increase maintenance costs.

Manufacturers

1. Current residual fuels should not be considered. Experience shows that this is not the approach to be compatible with reduced manning and maintainence.

2. Except for the engines with a 1100 - 1200° F turbine inlet temperature and with huge combustion chambers, there is no practical way at this time to burn residuals.

3. Technically it is feasible to burn pretreated residual fuel in a gas turbine, however, in a marine application it is presently economically impractical.

Combustion at or below the stoichiometric air/fuel ratio, although it is possible for short periods of time, is not feasible for constant applications because of the 3,000+° F temperatures associated. The nature of the gas turbine is such that it requires an excess of air in order to lower the turbine inlet temperature to the turbine material capability.

There is no way of allowing an equilibrium thickness of ash to deposit on the turbine blade. The ash deposits will continue to build up during constant power application, to the point where either thermal cycling or blade cleaning is required to prevent severe performance degradation along with corrosion problems.

4. Some of the latest research is aimed at reducing the need for a major portion of the pretreatment and corrosion and deposition reduction. Agree that lower temperatures and ash build up are not the way to go.

Others

1. It would seem that pretreatment of the residual fuel would be attractive.

8. Since the present methods of pretreatment of residual fuels involve a large first cost, large expenditure of volume and weight, require large amounts of distilled water and are not easy to completely automate, many of the advantages normally attributed to a gas turbine plant are lost when burning residual fuels.

	Agree	Agree in Part	Disagree	No Information
Users	45.4%	27.3%	9.1%	18.2%
Manuf.	50	10	30	10
Others	50	-	50	-
All	47.9	17.4	21.7	13.0

Comments:

Users

1. An R & D effort can greatly reduce the disadvantages stated for the fuel treatment process.

2. As evidenced by the Australian BHP steel container ships this is not even true now. With continued markets and system improvements, it will be less true in the future. The great majority of propulsion plants worldwide are Diesel I.C. Engines with fuel treatment plants.

Manufacturers

1. Don't think fuel treatment costs are that great. Normal bunker fuel handling takes lots of equipment - centrifuges, filters, day tanks, heaters --- and lots of labor to operate.

2. For marine applications, there is no practical way to burn residuals at this time.

3. Steam boilers have high maintenance costs when burning Bunker "C" or Navy Special.

4. Each part such as first cost volume and weight, water and automation are either exaggerations or half truths.

5. The gas turbine will be in a much better position competively if cleaner exhaust is required. The gas turbine is inherently a cleaner operating machine partially because of its design and partially because of the fuel it burns. In comparison, the gas turbine is cleaner than a diesel operating on the same fuel. The requirements for cleaner burning fuels will force all operators, including diesel, turbine and steam operators to either use cleaner fuel or pretreat the residual fuel as now required in gas turbine operation.

Others

1. Still may be economically attractive.

2. There appears to be no basic justification for the statement that many of the advantages of the gas turbine are lost when burning residual fuels.

9. Present second generation aircraft derivative gas turbines (such as LM 2500) have almost reached the maximum practical attainable thermal efficiency for simple open cycle gas turbines and any further significant reduction in specific fuel consumption for marine gas turbine plants will have to come through use of regenerative cycles or with waste heat boilers.

	Agree	Agree in Part	Disagree	No Information
Users	18.2%	27.3%	45.4%	9.1%
Manuf.	20	70	10	-
Others	-	50	-	50
All	17.4	47.8	26.1	8.7

Comments:

Users

1. True, at least for the near future.

2. Second generation engines have reached a plateau of efficiency limited by state-of-art in materials and blade cooling. Combined cycles offer further gains in efficiency.

3. Turbine inlet temperatures have not necessarily reached a theoretical limit at this time.

4. With the higher pressure ratios regeneration is no longer attractive.

5. Significant reductions in fuel rates through the use of regenerative cycles or other similar means may be difficult to achieve practically. Aircraft derivative gas turbines, while they may be used with a waste heat boiler, are

going to be extremely difficult to use with regenerative or similar equipment and in so doing some of the advantages of size and weight may be eliminated.

6. It is too early to rule out further improvements in materials and cooling techniques.

7. Although combined plants are more complicated and require larger space and weight they do appear to offer the best method for near term improvements in thermal efficiency for G.T. plants, primarily because U.S. Government sponsorship of large engine development is being slowed.

Manufacturers

1. Present second generation aircraft derivative gas turbines (such as LM 2500) have passed the maximum practical attainable thermal efficiency when operating in a marine atmosphere with marine fuels. High turbine inlet temperatures (between about 1600° F and 2000° F) although improving the thermal efficiency result in sulfidation problems in a salt air/heavy fuel environment.

Higher temperatures (above 2000° F) will only move the sulfidation problem to the after stages of the turbine section and will result in oxidation problems on the forward stages. The second generation gas turbines are currently having their turbine section changed out at about every 2,000 hours of operation. To be economically competitive, it is felt that longer TBO's are required.

2. Presently true, based on state-of-the-art and available materials.

3. Keep cycles simple and increase thermal efficiency through improved materials for higher turbine temperatures.

4. Pressure ratios of the LM 2500/JT9D are too high to make efficient use of a regenerator. Waste heat boilers will help if you need steam and can stand the bulk and volume.

5. Both compressor pressure ratio and turbine entry temperature can be increased. Limit is not reached yet.

6. True, for the next 8 - 10 years anyway.

7. This is true except for the fact that simple open cycle gas turbines will continue with the upward trend of higher TIT's.

8. Large turbines (open cycle) aren't too bad on SFC and a regenerative LM 2500 size engine would be a monster!

9. Aircraft derivatives with high compressor pressure ratios do not lend themselves to regeneration. Waste heat boilers are a must for application purposes and whether the units have reached their limits is yet a moot point.

Others

1. New cycles at 40:1 pressure ratio and near 3000° F inlet temperatures are under development. Efficiency possibly 45 to 50%.

10. The aircraft derivative gas turbine has a significant advantage over the heavy duty type in that the gas generator section can be easily removed allowing major overhauls to be done ashore and increasing the availability of the ship. Also the aero-derivative gas turbine performance can be improved by bringing the whole gas generator section up to date and making internal modifications to the power turbine to cope with the new gas generator.

	Agree	Agree in Part	Disagree	No Information
Users	45.4%	36.4%	9.1%	9.1%
Manuf.	70	20	10	-
Others	100	-	-	-
All	60.9	26.1	8.7	4.3

Comments:

Users

1. The aircraft prime mover companies have done an outstanding salesmanship job in capitalizing on what could have been a significant disadvantage to the gas turbine engine.

The immediate question is why would a shipowner or operator want to remove a prime mover at regular intervals? Prior to the present day acceptance of aircraft derivative engines in naval applications, was not all maintenance accomplished aboard ship or during regularly scheduled shipyard availabilities?

Where a gas turbine prime mover is used, the gas generator section (and the power turbine section also) must be

removed from the ship regularly, for there is no practical manner in which major maintenance items can be accomplished aboard ship. The high temperature, high performance section, the gas generator, even in aircraft service must be regularly overhauled, since it can not be designed (and should not be) for long life and achieve the performance required of the aircraft. In marine service the overhaul cycle will be less (1,000 to 6,000 hours) depending on the type of installation and load factor. The reduced overhaul cycle is dependent on how severe the environmental conditions are under which the engine must sustain operation. Removing the engine (and for the LM 2500, it is the complete engine) or gas generator (FT4 type installation) is clearly not an advantage to the shipowner or operator for he must have a replacement engine while the overhaul is being accomplished. However, it is not the disadvantage that it would have been many years ago. With ship crews (both merchant and naval) continually being reduced (because of the obvious economic considerations, as well as improved plant design and less skilled available labor) only a bare minimum of preventative maintenance is now accomplished aboard the ship itself.

In a life cycle cost analysis for a given ship mission, the aircraft engine's annual maintenance costs (including rotatable spare engines) are not much greater than steam or the industrial gas turbine and are less than a diesel plant for most ship applications. Thus, having to remove the engine from the ship is not a disadvantage but it is also not

an advantage.

In regard to modernizing the prime mover through regular removal and overhaul, the advantages gained are not completely clear, although ultimately there should be some. This question of modernization and conversion is misunderstood by many as it applies to a marine application. For aircraft, improvements gendered by technological advances (better materials, thus higher operating temperatures) can be directly used in producing greater engine thrusts and ultimately a better operating envelope if not totally improved performance capability. In a ship, these advantages are not always that apparent. The ship's hull, transmission system and propeller are designed, optimally hopefully, for a finite mission requirement. Thus a larger power capability available from a gas turbine can not be directly utilized in improving the ship performance. Engine improvements can be extremely beneficial if they result in lower fuel consumption rates and reduced maintenance requirements. From this standpoint the aircraft engine may have a slight advantage sometime in the future in comparison to the industrial gas turbine. The historical record to date would not substantiate this belief. All gas turbine engine marine installations have been subject to many changes, but primarily these have been the result of unsatisfactory operation in the marine environment.

2. The first part is true, particularly for naval ships. The heavy duty type has advantages which have not been

fully developed especially for merchant ships.

3. For a baseload plant, the life cycle cost advantage of the aero-derived turbine over the long-life industrial type has not yet been demonstrated.

4. The heavy duty G.T. can last much longer before overhauls are required.

5. While aircraft derivative turbines will be overhauled ashore, the price of such overhauls (much higher than anticipated) is one strike against the aircraft derivative engine.

Manufacturers

1. Agree, the complete gas generator can be changed out aboard ship if necessary in a few hours.

2. Depending on the changes/mods to the gas generator, major changes to the power turbine may be required.

3. Also on board maintenance is more easily performed.

4. Not too much info available - but the Adm. Callaghan had 4 gas generator changeouts in 17 months; between 3 - 5,000 hours/gas generator. The GTS John Sergeant on Bunker C after 9,800 hours, no overhaul, turbine in excellent condition. Maintenance is a big unknown yet to be proved.

Others

1. It is true that the aircraft type gas turbine has the advantage over the heavy duty type in quick replacement and also in updating with new technology.

11. Increasing the turbine inlet temperature of the regenerative cycle gas turbine to the 2300-2400° F range would give very attractive thermal efficiencies plus the increase in power per unit airflow would help negate the drawback of a bulky regenerator but this would require the development of high temperature heat transfer surfaces which doesn't appear likely in the near future.

	Agree	Agree in Part	Disagree	No Information
Users	9.1%	63.6%	9.1%	18.2%
Manuf.	50	30	20	-
Others	-	50	-	50
All	26.1	47.9	13	13

Comments:

Users

1. It is felt that a lower fuel price will open the market for gas turbines. Once more service experience is obtained, competitive R & D will soon find optimum cycle arrangements, better heat transfer surfaces, etc.

2. The total development of gas turbine (aircraft) engines and the required materials will be slowed in the future due to a reordering of national priorities. Government sponsorship of advanced technology for its own purpose will be more detailed considering total country cost benefit analyses.

Manufacturers

1. As previously pointed out temperatures in the

2300 to 2400° F range result in short turbine life. Also, unless the considerations are limited to low compression ratios (4-10) typical of industrial and centrifugal compressor units, the regenerative cycles, operating at the same turbine inlet temperatures, would not have enough of a performance improvement to warrant the additional cost and complexity of a regenerator.

2. Materials are available if applied.

3. Regenerators are usually found to be most useful in low pressure ratio, low temperature compressor gas turbines. Regenerators for high turbine entry temperatures to my knowledge are not now under development. The technology would be very complex.

4. First cost and maintenance cost of high temperature recuperator would probably be prohibitive.

5. Development should continue toward 2300 - 2400° F turbine inlet temperature for simple open cycle engines first then develop regenerators.

6. Lower power machines (4,000 hp) run close to 2300 - 2400° F now without regenerators. Cooled blades and nozzles are used most effectively and the effect on SFC is significant.

Others

1. High temperature and high pressure ratio go together, an optimized unit like the LM 2500 has a moderate exit gas temperature. Thus the gain from a regenerator is probably

less as P & T are increased together.

2. If the turbine inlet temperature is in the 2300 - 2400° F range, the thermal efficiency would be most attractive without the necessity and complexity of a regenerator.

12. "A regenerator is a mechanical monstrosity and will never be able to function properly in a marine environment."

	Agree	Agree in Part	Disagree	No Information
Users	-	-	90.9%	9.1%
Manuf.	20%	30%	50	-
Others	-	-	100	-
All	8.7	13.0	74.0	4.3

Comments:

Users

1. The unit has to be designed for cleaning and for replacement of sections as units.

2. It is a mechanical complication not a monstrosity. It should be able to operate in a marine environment, given good design and material selection.

Manufacturers

1. Means such as heat recovery boilers are much more practical for increasing thermal efficiency in a ship, specifically if they are used with high compression ratio aircraft derivative turbines. The only turbines that could efficiently utilize regeneration are the low pressure ratio industrial units which are inherently inefficient as a simple cycle unit.

2. Monster, yes - function? No reason why not.

3. Boilers are monstrosities also but because there were no alternatives, they were made to work.

4. Under certain circumstances, might be better

referred to as a "necessary evil".

Others

1. Disagree, but the regenerator may be too large and heavy to be attractive.

2. Regenerators have operated in marine environment. For example, the installation on the John Sergeant.

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